IEICE Proceeding Series

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Vol. 1 pp. 462-465
Publication Date: 2014/03/17
Online ISSN: 2188-5079

2012 International Symposium on Nonlinear Theory and its Applications
NOLTA2012, Palma, Majorca, Spain, October 22-26, 2012

Optical Signal Processing Using Nonlinear Period-One Dynamics of Semiconductor Lasers

Sheng-Kwang Hwang[1,2,*], Sze-Chun Chan[3], Yu-Han Hung[1], Shiuan-Li Lin[1], and Cheng-Hao Chu[1]

[1]Department of Photonics, National Cheng Kung University, Tainan, Taiwan
[2]Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan
[3]Department of Electronic Engineering, City University of Hong Kong, Hong Kong, China
*Email: skhwang@mail.ncku.edu.tw

Abstract– A semiconductor laser under nonlinear period-one dynamics is demonstrated for both optical frequency conversion and optical modulation format conversion. Such conversions depend solely on the dynamical interaction between the input signal and the injected laser. Only a typical laser is therefore required as the main conversion unit. A wide dynamic range of the input modulation depth is feasible. By adopting different spectral components, different output modulation depths can be obtained. These characteristics make the proposed system flexible and re-configurable.

1. Introduction

Nonlinear dynamics of semiconductor lasers has attracted much research attention over the past decades. Owing to its unique characteristics [1-5], the development of nonlinear dynamics in semiconductor lasers for technological applications has led to many interesting and important functionalities. For example, stable locking dynamics has been demonstrated for high-frequency microwave generation and transmission [6,7]. Chaotic dynamics has been proposed for cryptography [8,9], and high-speed random bit generation [10].

Recently, period-one (P1) dynamics has attracted much interest for photonic microwave applications [11-14]. In addition, it has also attracted increasing attention for optical signal processing applications. For example, we have shown that conversion from optical amplitude-shift keying (ASK) to microwave frequency-shift keying (FSK) can be achieved [15]. This functionality is useful for radio-over-fiber systems where an interface between the optical and wireless networks is required for such conversion to ensure transmission transparency. In this study, we present two other functionalities of optical signal processing based on P1 dynamics of semiconductor lasers, that is, optical frequency conversion [16] and optical modulation format conversion.

Due to the continuous demand for higher transmission capacity in optical communications, a variety of schemes have been proposed, including wavelength division multiplexing (WDM) and advanced optical modulation formats. On one hand, to resolve frequency contention and allow optical cross-connect in WDM networks, the signal processing functionality of optical frequency conversion is required [17]. On the other hand, since optical modulation formats other than conventionally adopted ASK, such as FSK [18] and phase-shift keying (PSK) [19], would be adopted for different optical networks depending on their scales and applications, optical modulation format conversion becomes a necessary signal processing functionality bridging different optical networks [20,21]. To provide alternative solutions for these functionalities, P1 dynamics of semiconductor lasers is proposed and demonstrated in the present work.

2. Proposed System and Principle

The proposed system of optical signal processing basically consists of one semiconductor laser oscillating at a free-running frequency, ν_1, as shown in Fig. 1. An optical carrier at $\nu_2 = \nu_1 + f$, where f is the detuning frequency, from a remote optical network injects into the laser for conversion of its optical frequency or optical modulation format. The injection strength ξ, defined as the normalized field strength injected into the laser, can be controlled by the optical power adjuster to achieve the preferred performance characteristics, as addressed below. Such optical injection pulls the intracavity field oscillation of the laser and thus leads to the regenerative amplification at ν_2 at the laser output. In addition, the necessary gain for the laser is reduced due to external injection, leading to the increase of the cavity refractive index and thus resulting in the frequency red-shift of the cavity resonance from ν_1 toward ν_{cr}. Such injection-shifted cavity resonance competes dynamically with the injection-imposed laser oscillation, which radically modifies the

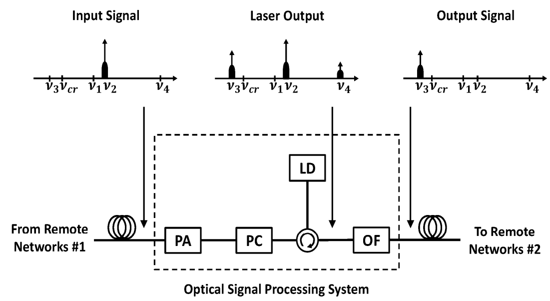

Fig. 1. Schematic of the proposed system (bottom) and optical spectra at the system input, laser output, and system output (top). LD, laser diode; PA, power adjuster; PC, polarization controller; OF, optical filter. ν_1, free-running frequency of the laser; ν_2, optical injection frequency; ν_3 and ν_4, induced frequencies; ν_{cr}, red-shifted cavity resonance frequency.

conditions, i.e. ξ and f, this competition would lead to the emergence of sidebands at ν_3 and ν_4 at the laser output, giving rise to P1 dynamics [4,5]. Clearly, the emerged sideband at either ν_3 or ν_4 can serve as a duplicate of the input optical carrier at another frequency. The question now is whether the data carried by the input optical carrier at ν_2 is encoded onto the output optical carrier at ν_3 or ν_4.

To answer this question, let us study the lower sideband at ν_3. Interestingly, it is demonstrated [5,7,13] that the lower sideband at ν_3 always appears close to but lower than the shifted cavity resonance at ν_{cr}, implying that the former is largely determined by the latter. This suggests that the cavity resonance shift, which strongly depends on the index increment, or equivalently the gain reduction, plays a key role in determining the dynamical states and the corresponding spectral signatures of the proposed system. Since the index increment as well as the gain reduction depends on the characteristics of the injection signal, the amplitude, phase, and frequency of all spectral components of P1 dynamics generally depend on the characteristics of the injection signal. For example, if the input optical carrier temporally varies in ASK, the optical gain and refractive index of the laser would change accordingly, which thus encodes such ASK on all spectral components. Through proper optical filtering, an optical carrier at, for example, ν_3 carrying the same ASK data can be obtained at the system output, therefore achieving optical frequency conversion. The same principle applies to the input optical carrier varying in FSK or PSK. Thus, optical frequency conversion can be achieved for input optical signals with any data format.

For the input optical carrier varying in ASK, since both the optical gain and refractive index of the laser change accordingly, spectral components of P1 dynamics would vary in not only amplitude but also frequency. This suggests that by suppressing ASK and by decoding FSK

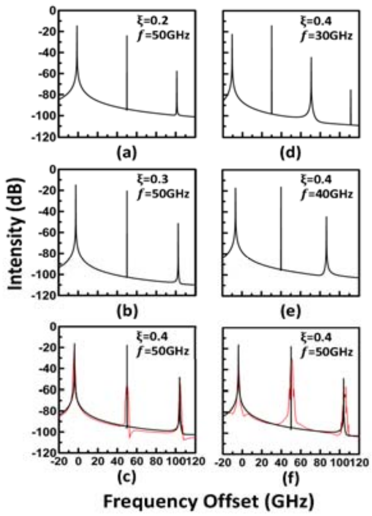

Fig. 2. Optical spectra of P1 dynamics under different injection conditions. Black curves show spectra for unmodulated injection. Red curves in (c) and (f) show spectra for ASK- and FSK-modulated injection, respectively, where bit rate = 2.5 Gb/s and modulation index = 0.1 for ASK and 0.5 for FSK. The axes are relative to the intensity and frequency of the free-running laser.

of the spectral component at ν_3, for example, modulation format conversion from optical ASK to optical FSK can be achieved at the system output. Similarly, for the input optical signal varying in FSK, the spectral components vary in not only frequency but also amplitude, suggesting modulation format conversion from optical FSK to optical ASK. This format conversion principle, however, does not apply to PSK. Hence, by using the same system, optical modulation format conversion between optical ASK and optical FSK can also be achieved.

3. Results and Analyses

For the following analyses, numerical calculation based on conventional rate equations characterizing a single-mode semiconductor laser subject to optical injection is conducted [4,16]. A second-order Runge-Kutta method with experimentally obtained laser parameters [6] is used to carry out the calculation. Let us first study optical spectra of the P1 dynamics under different conditions of injection with no data, as shown in Fig. 2. For each injection condition, the input optical signal not only locks the laser at the injection frequency but also induces sidebands. The induced sidebands are equally separated in frequency from the injection and are highly asymmetric in intensity. In addition, the frequency and intensity of each spectral component strongly depend on ξ and f. In fact, the intensity and frequency of each frequency component depend on ξ and f continuously and monotonically, as clearly demonstrated in Fig. 3.

3.1. Optical Frequency Conversion

The frequency of each spectral component in Fig. 3 suggests that an input optical carrier at the injection frequency could lead to an output optical carrier at another frequency, achieving optical frequency conversion. The frequency shift can be adjusted from tens to hundreds of gigahertz by controlling ξ and f [4,13], making the proposed system with the re-configurability for different required conversion range in different optical networks.

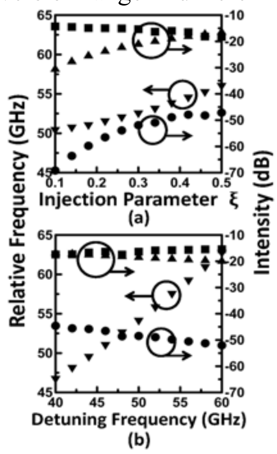

Fig. 3. Frequency and intensity of each frequency component in terms of (a) ξ under f = 50 GHz and (b) f under ξ = 0.4. The relative frequency is defined with respect to the injection frequency and thus the frequency of the central component is zero. Down-triangles: both sidebands; squares: lower sidebands; circles: upper sidebands; up-triangles: central components.

The static characteristics shown in Fig. 3 also suggest that a dynamical variation in the level or frequency of the injection would, respectively, lead to a dynamical change in the intensity or frequency of each frequency component. This implies that frequency conversion can be carried out for input optical signals with not only ASK but also FSK and PSK. Spectra of the laser under modulated optical injection are shown in Figs. 2(c) and 2(f). Compared with the spectra for unmodulated injection, spectral broadening of each frequency component appears while the key signature of the P1 dynamics is mainly preserved. This suggests that the data, either ASK, FSK, or PSK, carried by the input optical carrier is encoded on each spectral component. This also suggests that frequency down-, no-, and upconversion, which are equivalent to the lower sideband, central component, and upper sideband, respectively, can be simultaneously achieved.

To further demonstrate the feature of modulation format transparency for the proposed system, the ASK and FSK indeices of the output signal in terms of those of the input signal are shown in Figs. 4(a) and 4(b), respectively. The modulation depth dependence is linear, resulting in a wide dynamic range of the input modulation depth. The extent of the dependence is, however, different for different spectral components. This indicates that different output modulation depths at a fixed input modulation depth can be obtained by adopting different frequency components. Similar observations of the modulation depth dependence are also found for the case of PSK and for other injection conditions under study.

To study the quality of the frequency-converted data, the bit-error ratio (BER) as a function of signal-to-noise ratio (SNR) is shown in Figs. 5(a) and 5(b). BER of the data-modulated input optical signal is also shown as the solid curve for comparison. BER down to 10^{-12} is achieved for all cases under study. In addition, the BER curves follow closely with those of the corresponding injection signal, showing a slight power penalty. Similar observations are also found for the case of PSK and for other injection conditions under study.

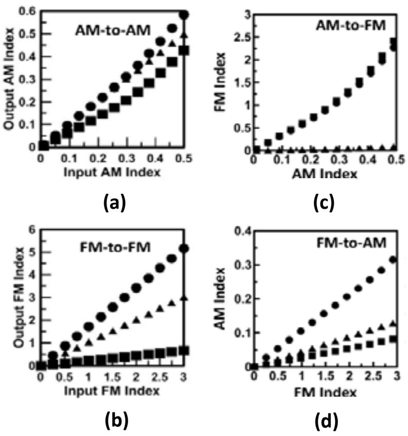

Fig. 4. Output modulation index in terms of input modulation index for optical frequency conversion (a) and (b), and for optical modulation format conversion (c) and (d) under $\xi = 0.4$, $f = 50$ GHz, and the modulation frequency $f_m = 2.5$ GHz. Squares: lower sidebands; circles: upper sidebands; up-triangles: central components.

3.2. Optical Modulation Format Conversion

As shown in Fig. 3, a dynamical variation in the level or frequency of the injection, in fact, leads to a dynamical change in not only the intensity but also the frequency of each spectral component. This suggests that, for induced spectral components, an ASK input optical signal at one carrier frequency could lead to a FSK outgoing optical signal at another carrier frequency and vice versa, thus carrying out conversion between ASK and FSK. For the central component, however, only FSK-to-ASK conversion can be achieved with the characteristic of no-shift in the carrier frequency.

The modulation depth of the output signal depends on that of the input signal, as shown in Figs. 4(c) and (d). Such modulation depth dependence is linear, resulting in a wide dynamic range of the input modulation depth. The extent of the dependence is, however, generally different for different spectral components, particularly for FSK-to-ASK conversion. Clearly, ASK-to-FSK conversion cannot be carried out by using the central component. Similar observations of the modulation depth dependence are also found for other injection conditions under study. Therefore, based on these observations, different output modulation depths at a fixed input modulation depth can be achieved by adopting different spectral components.

The quality of the modulation-format-converted data is shown in Figs. 5(c) and 5(d). BER down to 10^{-12} is achieved for all cases under study. In addition, the BER curves follow closely with those of the corresponding injection signal, showing a slight power penalty. Similar observations are also found for other injection conditions under study.

4. Conclusion

A semiconductor laser operating at the P1 nonlinear dynamics through proper optical injection is demonstrated for optical frequency conversion and optical modulation

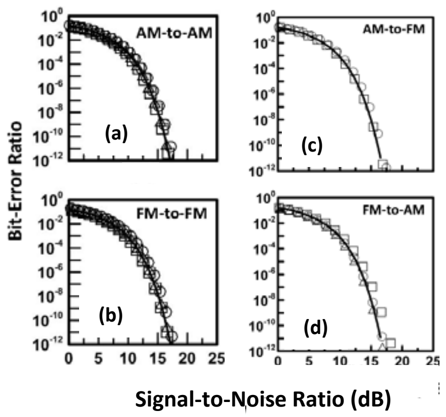

Fig. 5. BER versus SNR for optical frequency conversion (a) and (b), and for optical modulation format conversion (c) and (d). Note that $\xi = 0.4$, $f = 50$ GHz, bit rate = 2.5 Gb/s, ASK index = 0.1, and FSK index = 0.5. Squares: lower sideband; circles: upper sideband; up-triangles: central component.

format conversion. Both conversions depend solely on the dynamical interaction between the input signal and the injected laser, and therefore only a typical semiconductor laser is necessary as the main conversion unit where no extra optical beam or microwave generator is required as in most other proposed schemes. A wide dynamic range of the input modulation depth is feasible. Different output modulation depths can be achieved by adopting different spectral components. For optical frequency conversion, the proposed scheme provides the capability of modulation format transparency, which makes it reconfigurable for future optical networks adopting different modulation formats and which was only possible previously through the four-wave mixing scheme. For optical modulation format conversion, both ASK-to-FSK and FSK-to-ASK conversions can be achieved using the same system. In addition, frequency shifts of the optical carrier can also be achieved, which allows simultaneous frequency conversion of the optical carrier if required.

Acknowledgments

S.K. Hwang's work was supported by the National Science Council of Taiwan under Contract NSC99-2112-M-006-013-MY3. S. C. Chan's work was fully supported by a grant from the City University of Hong Kong under Project 7002674.

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