All-Optical Modulation Format Conversion Using Nonlinear Dynamics of Semiconductor Lasers

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***Abstract*— Under proper injection of an incoming optical signal to be format-converted, a semiconductor laser can be driven at period-one dynamics due to the dynamical competition between the injection-imposed laser oscillation and the injection-shifted cavity resonance. Equally separated spectral components therefore emerge, the intensity and frequency of which strongly depend on the intensity and frequency of the incoming optical signal. Optical modulation format conversion between amplitude-shift keying (ASK) and frequency-shift keying (FSK) can thus be achieved by applying such a mechanism. The conversion depends solely on the property of the incoming optical signal for a given laser and therefore only a typical semiconductor laser is necessary as the key conversion unit. Due to the unique underlying mechanism, both ASK-to-FSK and FSK-to-ASK conversions can be achieved using the same system. The bit-error ratio at 10 Gb/s is observed down to 10^{-12} with a slight power penalty for both conversions. Simultaneous frequency conversion of the incoming optical carrier is also possible. By adopting different spectral components or different injection conditions, different output modulation indices can be obtained.**

***Index Terms*— Modulation format conversion, nonlinear dynamics, optical communications, optical injection, optical signal processing, semiconductor lasers.**

I. Introduction

WHILE solitary single-mode semiconductor lasers normally emit continuous-wave radiation, their rich nonlinear dynamics, such as stable locking, self-mixing, periodic oscillations, and chaos, can be excited with various perturbation schemes [1]–[9]. These highly complex dynamical characteristics can be well controlled by properly adjusting the experimentally accessible parameters of perturbations. Therefore, the ability to control the dynamical behavior of semiconductor lasers, 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, stable locking dynamics has been demonstrated for high-frequency microwave generation and transmission [10]–[14] which are critical for future high-capacity optical communications and radio-over-fiber access networks. Self-mixing dynamics has been studied for metrology, sensing, physical quantity measurement, and laser parameter measurement [15], [16]. Chaotic dynamics has been proposed for cryptography [17]–[20], high-speed random number generation [21], [22], and high-resolution ranging and imaging [23], [24].

Lately, period-one (P1) nonlinear dynamics has attracted much research interest for photonic microwave applications [25], such as photonic microwave oscillators [26]–[30] and radio-over-fiber downlinks and uplinks [31]–[33]. On the other hand, it has also attracted increasing research attention for optical signal processing applications. We have, for example, demonstrated that optical frequency conversion is feasible by taking advantage of P1 dynamics [34], where optical frequency down-, no-, and up-conversion can be simultaneously or individually achieved by using a typical semiconductor laser. The optical modulation format of the data is maintained after conversion, which applies to not only amplitude-shift keying (ASK) but also frequency-shift keying (FSK) and phase-shift keying (PSK). Most other proposed schemes, however, can only carry out optical frequency conversion for ASK data only. Therefore, the capability of modulation format transparency makes the P1-dynamics scheme very attractive for future all-optical networks [35]. We have also shown that conversion from optical ASK to microwave FSK can be achieved by taking advantage of P1 dynamics [36], which is applicable to microwave signals of up to hundreds of gigahertz by using a typical semiconductor laser. This functionality is particularly useful for radio-over-fiber systems where optical and wireless networks are connected. An interface between the two different networks is required to carry out such conversion to ensure transmission transparency since optical networks conventionally transmit ASK baseband optical signals while wireless networks commonly radiate FSK microwave signals. In this study, we propose to use P1 dynamics of semiconductor lasers for another functionality of optical signal processing, that is, modulation format conversion between optical ASK and optical FSK.

Motivated by the continuous demand for higher data capacity and longer transmission distance per unit cost, many advanced optical modulation formats have been proposed

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over the past years [37]. They have been demonstrated to outperform the conventionally adopted ASK in terms of receiver sensitivity, spectral efficiency, and tolerance to fiber dispersion and nonlinearity. While many research efforts have been devoted to the investigation of PSK, recent studies on FSK have attracted great research interest [38]–[42] because of its promising advantages for various network applications. On one hand, for example, FSK could be adopted for downlink transmission in optical access networks to take advantage of its unique characteristics of distinct modulation sidebands and constant intensity [43]–[47]. While the former allows the demodulation of FSK through simple optical filtering, the latter allows the reuse of optical carriers for uplink transmission. On the other hand, FSK, particularly the so-called minimum-shift keying format, possesses more compact spectrum and lower side-lobes compared with differential PSK, which thus provides higher spectral efficiency, larger dispersion tolerance, better crosstalk reduction, and stronger nonlinearity immunity [48]–[52]. Therefore, FSK could be considered as another solution for long-haul, high-capacity optical networks.

As noted above, future optical communication networks would adopt different optical modulation formats depending on their scales, applications, and costs. When optical signals are transmitted between different networks, conversion between different optical modulation formats becomes a key functionality for transparent network interconnection. For example, while FSK could be employed for long-haul backbones and access networks, respectively, as suggested above, ASK could be used for metro/regional networks due to its simplicity and cost-effectiveness in generation and detection. Therefore, conversion between ASK and FSK at nodes connecting between backbones and metro networks or between metro networks and access networks is required. In fact, a variety of all-optical conversion schemes based on different photonic devices and nonlinearities have been proposed [53]–[56], which however mainly focus on conversion from optical ASK to optical PSK. Therefore, in this study, we propose to use P1 dynamics of semiconductor lasers for modulation format conversion between optical ASK and optical FSK through numerical simulation.

As will be observed in the following discussions, conversion between optical ASK and optical FSK depends solely on the property of the incoming optical signal by taking advantage of P1 dynamics of a given laser. Only a typical semiconductor laser is therefore required as the key conversion unit, where no extra optical beam or microwave generator is necessary as required in many other schemes. Due to the unique underlying mechanism, both ASK-to-FSK and FSK-to-ASK conversions can be achieved using the same system. In addition, different output modulation indices and different frequency shifts of the optical carrier can also be achieved. The latter allows simultaneous frequency conversion of the optical carrier if required. These characteristics may increase the flexibility and re-configurability of the proposed system.

The remainder of this paper is outlined as follows. In Section II, the conversion principle and the underlying mechanism of the proposed P1-dynamics scheme are addressed. Coupled rate equations characterizing the dynamics of a single-mode semiconductor laser subject to external optical injection is described in Section III, where experimentally measured values of laser intrinsic parameters are introduced. In Section IV, numerically obtained results and analyses are presented. Finally, discussion and conclusion are made in Section V.

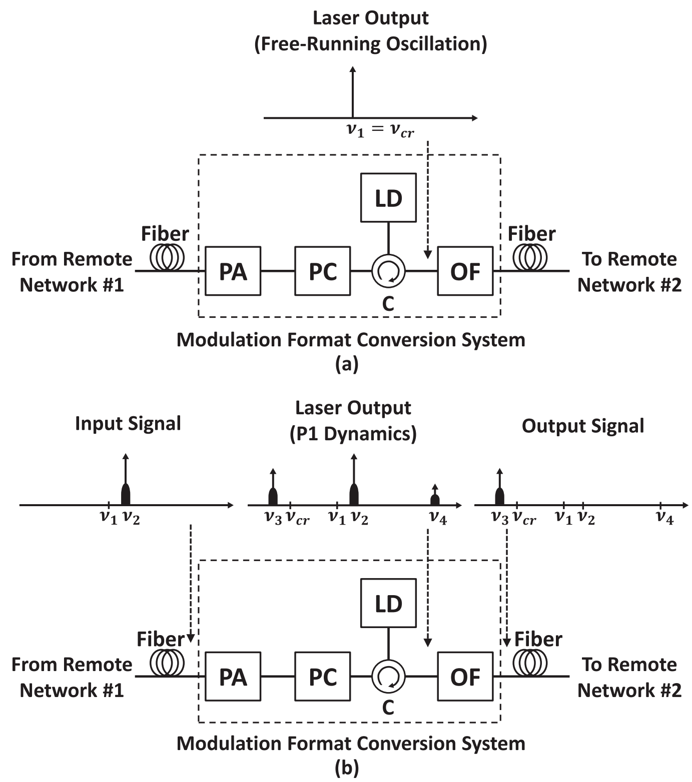

Fig. 1. Schematic configuration and spectra of the proposed conversion system when the input signal is (a) off and (b) on. ν_1: free-running frequency of the laser. ν_2: optical injection frequency. ν_3 and ν_4: induced sideband frequencies. ν_{cr}: cavity resonance frequency. LD: laser diode. PA: power adjuster. PC: polarization controller. C: fiber circulator. OF: optical filter.

II. Conversion Principle

A schematic configuration of the proposed conversion system is shown in Fig. 1, which consists of one semiconductor laser as the key conversion unit. Under the free-running condition shown in Fig. 1(a), the laser oscillates at the cavity resonance frequency, $\nu_{cr} = \nu_1$. When an optical signal at ν_2 carrying data from the remote network injects into the system, as shown in Fig. 1(b), the dynamics of the laser would be perturbed. To excite a proper nonlinear dynamical state, the polarization and power of the input optical carrier are adjusted, respectively, through a polarization controller and a power adjuster which may consist of both an optical amplifier and an optical attenuator. While the optical injection progressively locks the optical phase of the laser, it pulls the intracavity field oscillation of the laser away from the free-running cavity resonance, ν_1, toward ν_2. Such an injection pulling effect is generally observed in oscillators that are described by the Adler's equation [57]. However, due to the unique nature of the semiconductor laser, such an injection pulling effect competes with another effect, the red-shifting effect [14], [32], [58], [59]. The introduction of the external field reduces the necessary gain for the laser from its free-running value, leading to the increase in the refractive index of the laser cavity through the antiguidance effect. This red-shifts the cavity resonance from its free-running value, which therefore attempts to pull the intracavity field oscillation of the laser toward the shifted cavity instead. Such a dynamical competition between the injection-imposed laser oscillation and the injection-shifted cavity resonance radically modifies the dynamics of the laser.

Under certain injection levels and frequencies, the relaxation resonance of the laser is undamped through Hopf bifurcation and equally-spaced sidebands at ν_3 and ν_4 therefore sharply emerge, which is a typical signature of P1 nonlinear dynamics [3], [9], [60], [61]. Since the laser cavity resonance red-shifts, the lower sideband is resonantly enhanced, resulting in the intensity-asymmetry of the sidebands. In fact, the lower sideband appears close to but lower than the red-shifted cavity resonance, suggesting that the former is largely determined by the latter [14], [32], [59]. Since the extent of optical gain reduction of the laser and consequently the extent of refractive index enhancement of the laser are strongly determined by the injection level and frequency, the level of cavity resonance red-shift and thus the intensity and frequency of each sideband considerably depend on such injection conditions as well. This suggests that if an incoming optical signal varies dynamically in its amplitude or frequency, such as in ASK or FSK, respectively, the optical gain and refractive index of the laser would be both altered according to such dynamical variation. This could encode the data carried by the incoming optical signal on both sidebands with both ASK and FSK formats. By optically selecting one sideband and by properly suppressing the residual ASK or FSK modulation, all-optical modulation format conversion for either ASK-to-FSK or FSK-to-ASK can be achieved.

III. Theoretical Model

The proposed converter can be modeled by the following normalized rate equations of a single-mode semiconductor laser subject to optical injection [62], [63]:

$$\frac{da}{dt} = \frac{1}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p(2a+a^2)\right](1+a) + \xi\gamma_c\left[1+s_{ASK}(t)\right]\cos\left[\Omega t+\phi+s_{FSK}(t)\right] \quad (1)$$

$$\frac{d\phi}{dt} = -\frac{b}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p(2a+a^2)\right] - \frac{\xi\gamma_c\left[1+s_{ASK}(t)\right]}{1+a}\sin\left[\Omega t+\phi+s_{FSK}(t)\right] \quad (2)$$

$$\frac{d\tilde{n}}{dt} = -\gamma_s\tilde{n} - \gamma_n(1+a)^2\tilde{n} - \gamma_s\tilde{J}(2a+a^2) + \frac{\gamma_s\gamma_p}{\gamma_c}\tilde{J}(2a+a^2)(1+a)^2. \quad (3)$$

Here, a and $\tilde{n}$ are the normalized field amplitude and carrier density of the injected laser, respectively, while ϕ is the phase difference between the injection field and the injected laser. Laser intrinsic parameters, γ_c, γ_s, γ_n, γ_p, and b are the cavity decay rate, spontaneous carrier relaxation rate, differential carrier relaxation rate, nonlinear carrier relaxation rate, and linewidth enhancement factor, respectively. The normalized bias current, $\tilde{J}$, represents the bias level above the threshold of the injected laser. The injection parameter, ξ, is proportional to the ratio of the optical fields between the injection signal and the free-running laser, the square of which is proportional to the injection power actually received by the laser. The detuning frequency, $f = \Omega/2\pi$, is the frequency offset of the injection from the free-running frequency of the laser. The data carried by the injection signal is described in Eqs. 1 and 2 by $s_{ASK}(t) = mg(t)$ for ASK and $s_{FSK}(t) = 2\pi f_m \int mg(t)dt$ for FSK, respectively, where m is the modulation index, f_m the modulation frequency, and $g(t)$ the information.

The values of the intrinsic parameters adopted in this study are $\gamma_c = 5.36 \times 10^{11}$ s^{-1}, $\gamma_s = 5.96 \times 10^9$ s^{-1}, $\gamma_n = 1.84 \times 10^{10}$ s^{-1}, $\gamma_p = 4.69 \times 10^{10}$ s^{-1}, and $b = 3.2$. These values were experimentally determined in our previous work [11] where the laser was biased at 72 mA, corresponding to $\tilde{J} = 3$, with an output power of 11 mW. The corresponding relaxation resonance frequency is given by $(2\pi)^{-1}(\gamma_c\gamma_n + \gamma_s\gamma_p)^{1/2} \approx$ 16.03 GHz. A second-order Runge-Kutta method with the measured laser parameters is used to solve Eqs. (1)–(3), which has been demonstrated to reproduce all the experimentally observed phenomena in such a laser system [3], [5], [60]. Depending on the level and frequency of the optical injection, the injected laser can undergo a variety of different dynamical states [3]–[5], [9], [64], [65] because of the radical modification in laser dynamics, as previously discussed. For our interest in this study, the laser system is operated at P1 dynamics under various combinations of injection level and frequency. The validity of the theoretical model described above has been verified with experimental data for the range of the injection level and frequency considered in this study [14], [32], [36].

IV. Results and Analyses

Figure 2 demonstrates numerically obtained optical spectra of the P1 dynamics in terms of ξ (left column) and f (right column) under a fixed f and ξ, respectively, when the incoming optical signal carries no data. Note that the axes are relative to the intensity and frequency of the laser under the free-running condition, respectively. As observed, for each injection condition, not only a regeneratively amplified signal appears at the injection frequency due to the injection pulling effect but also undamped sidebands equally separated from the injection frequency emerge due to the red-shifting effect. The induced sidebands are highly asymmetric in intensity due to the red-shifted cavity resonance enhancement at the lower sideband. Such P1 dynamics is observed over a large range of injection level and frequency [3], [9], [60], [61]. As also observed, the frequency and intensity of each spectral component strongly depend on both the level and frequency of the incoming optical signal. For example, on one hand, the lower sideband approximately shifts from −1 GHz to −6 GHz and shrinks from −14 dB to −15 dB when ξ is changed from 0.15 to 0.35 at $f = 50$ GHz. On the other hand, it approximately moves from −14 GHz to −6 GHz and grows from −18 dB to −15 dB when f is varied from 30 GHz to 50 GHz at $\xi = 0.35$.

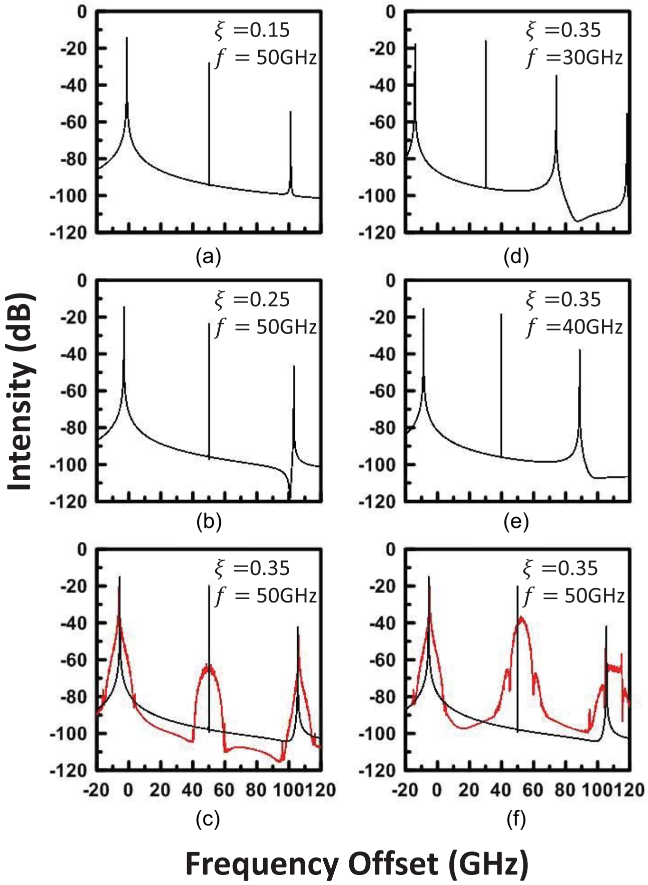

Fig. 2. (a)–(f) Spectra of P1 dynamics under different injection conditions. Black curves in all plots show spectra under unmodulated injection. Red curves in (c) and (f) show spectra under ASK- and FSK-modulated injection, respectively, where the bit rate is kept at 10 Gb/s and $m = 0.1$ for ASK and 0.5 for FSK. The x- and y-axes are relative to the frequency and intensity, respectively, of the free-running laser.

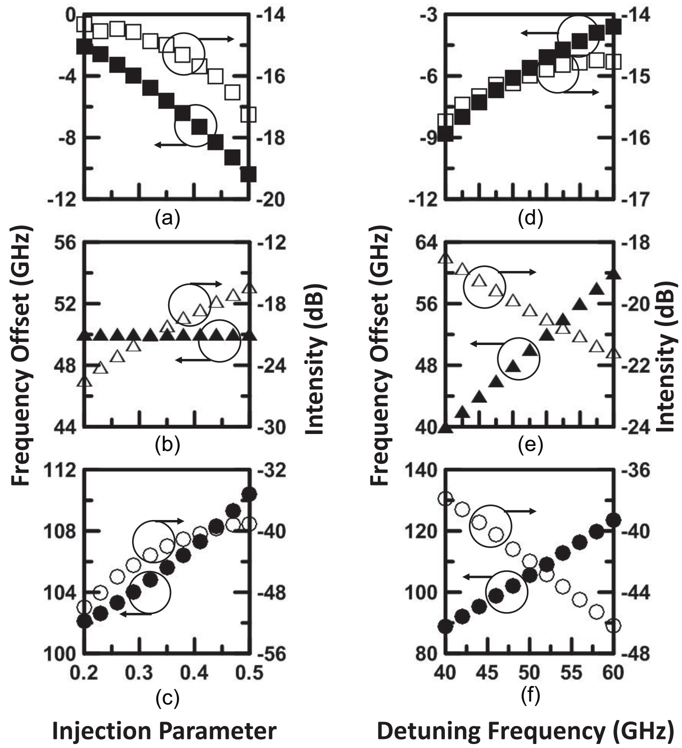

Fig. 3. Frequency and intensity of each spectral component in terms of (a)–(c) ξ under $f = 50$ GHz and (d)–(f) f under $\xi = 0.35$. Squares: lower sidebands. Up-triangles: central components. Circles: upper sidebands. Note that intensity and frequency are calculated relative to that of the free-running laser.

Such dependence of the intensity and frequency of each spectral component on injection level and frequency is, in fact, continuous and monotonic, as clearly demonstrated in Fig. 3. These static characteristics of the P1 dynamics suggest that a dynamical variation in either the level or the frequency of the injection would lead to a dynamical change in the intensity and frequency of each frequency component. This indicates that, for sidebands, an incoming optical signal with ASK modulation at one carrier frequency could lead to an outgoing optical signal with FSK modulation at another carrier frequency and vice versa, thus carrying out conversion between optical ASK and optical FSK. The corresponding shift in carrier frequency depends on the injection condition, which ranges from a few gigahertz to tens of gigahertz [32]. The residual ASK or FSK modulation can be suppressed experimentally through the gain saturation or cross-phase modulation of semiconductor optical amplifiers, respectively [66], [67]. For the central component, however, such conversion can be achieved with the characteristic of no-shift in the carrier frequency.

To understand the conversion response of the laser system subject to either ASK- or FSK-modulated injection, dynamical characteristics of each spectral component are next studied under different modulation depths and frequencies. Figure 4 shows the modulation index of the output optical signal as a function of that of the input optical signal for conversions to the lower sideband, central component, and upper sideband. For Figs. 4(a)–(b) and Figs. 4(c)–(d), the modulation frequency f_m is increased from 10 GHz to 20 GHz, respectively, where the injection detuning frequency is also adjusted accordingly from 50 GHz to 100 GHz. From the plots in Fig. 4, the output modulation index strongly depends on the input modulation index irrespective of the modulation frequency. Such dependence is approximately linear for both ASK-to-FSK and FSK-to-ASK conversions, resulting in a wide dynamic range of the input modulation index. The extent of the dependence is, however, generally different for different spectral components. The squares of Fig. 4 correspond to conversion to the lower sideband. As previously addressed, the lower sideband originates from the red-shifted cavity resonance of the optically injected laser. It usually emerges near the free-running laser oscillation frequency, as shown in Fig. 2, for injection conditions considered in this study. The dynamical response associated with the lower sideband thus reduces when the modulation frequency increases beyond the relaxation resonance frequency, as in the case of modulating a free-running laser. Therefore, comparing the squares of Figs. 4(a)–(b) to those of Figs. 4(c)–(d) reveals that the output modulation index clearly reduces as the modulation frequency f_m increases from 10 GHz to 20 GHz, where the relaxation resonance frequency is kept at 16.03 GHz. On the other hand, the up-triangles in Fig. 4 correspond to conversion to

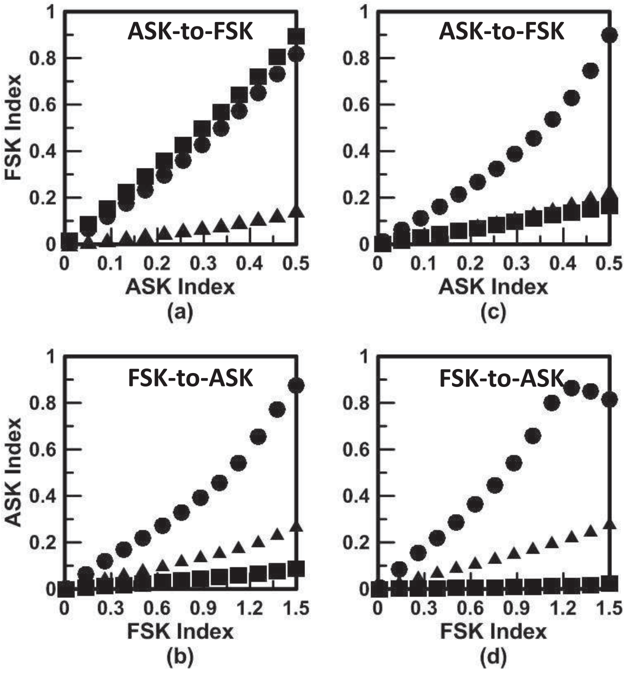

Fig. 4. (a) and (b) Output modulation index in terms of input modulation index under $\xi = 0.35$, $f = 50$ GHz, and $f_m = 10$ GHz. (c) and (d) Output modulation index in terms of input modulation index under $\xi = 0.35$, $f = 100$ GHz, and $f_m = 20$ GHz. Squares: lower sidebands. Up-triangles: central components. Circles: upper sidebands.

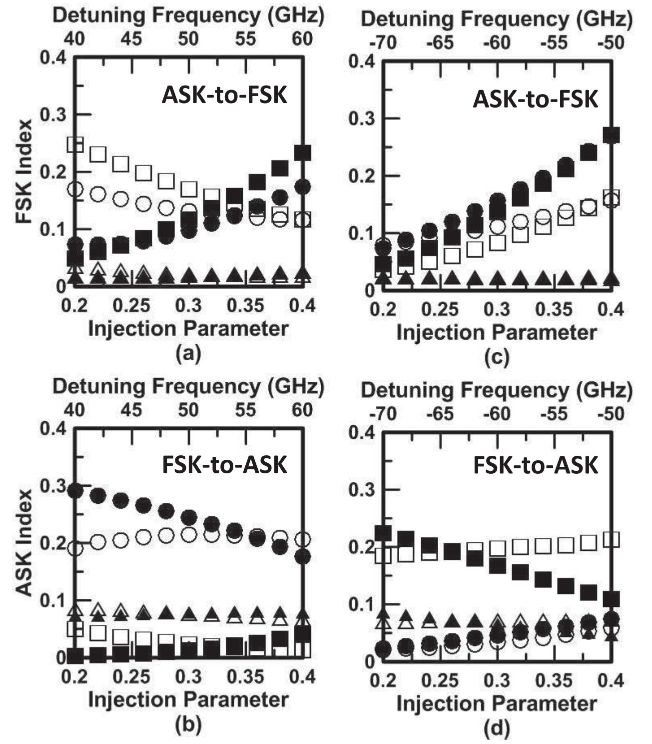

Fig. 5. (a) and (b) Output modulation index in terms of ξ when $f = 50$ GHz (solid symbols) and in terms of f when $\xi = 0.35$ (open symbols) for P1 dynamics above the Hopf bifurcation boundary. (c) and (d) Output modulation index in terms of ξ when $f = -60$ GHz (solid symbols) and in terms of f when $\xi = 0.25$ (open symbols) for P1 dynamics below the locking-unlocking boundary. Squares: lower sidebands. Up-triangles: central components. Circles: upper sidebands. For input signals, $m = 0.1$ for ASK, $m = 0.5$ for FSK, and $f_m = 10$ GHz.

the central component. The central component is generally detuned far away from the free-running laser oscillation and so mainly originates from regenerative amplification of the input optical signal. As a result, the output modulation index is not very sensitive to the modulation frequency, according to the triangles in Fig. 4. Similarly, the circles in Fig. 4 correspond to conversion to the upper sideband that originates from nonlinear wave-mixing of the central component and the emission of the slave laser, which is also not very sensitive to the modulation frequency. In short, ASK-to-FSK and FSK-to-ASK conversions can generally be achieved, although the modulation frequency for converting into the lower sideband is limited by the relaxation resonance frequency.

Similar observations of the modulation index dependence are also found for other injection conditions under study. In fact, the output modulation index depends strongly on the injection condition, as shown in Figs. 5(a) and (b). Such dependence varies continuously and monotonically for both conversions. However, different spectral components generally exhibit different levels of the output modulation index dependence on injection condition. Therefore, based on these observations, it is possible to achieve different output modulation indices at a fixed input modulation index by adopting different frequency components or different injection conditions. The P1 dynamics under different injection conditions discussed so far appears above the Hopf bifurcation boundary where the detuning frequencies are mostly positive [14], [32], [60], [61]. A similar P1 dynamic behavior also occurs below the locking-unlocking boundary where the detuning frequencies are mostly negative. Figs. 5(c) and (d) shows the output modulation index dependence on injection condition within that region. Similar observations are found as well, demonstrating the feasibility of applying P1 dynamics below the locking-unlocking boundary for both ASK-to-FSK and FSK-to-ASK conversions as well and thus considerably expanding the allowable frequency range of the input optical carrier.

Optical spectra of the P1 dynamics under ASK- and FSK-modulated injection at $\xi = 0.35$ and $f = 50$ GHz are also shown in Figs. 2(c) and (f), respectively. 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. To study the quality of the format-converted data under $\xi = 0.35$ and $f = 50$ GHz, the bit-error ratio (BER) as a function of signal-to-noise ratio (SNR) is shown in Figs. 6(a) and (b). To numerically obtain BER, a conventional scheme based on calculating the error function of the Q-factor of the demodulated data [68]–[70] is adopted in this study, where white channel noise with Gaussian statistics is considered. BER of the data-modulated incoming 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. Eye diagrams for the upper sideband at BER of 10^{-9} are shown in Figs. 6(c) and (d), where clear eye

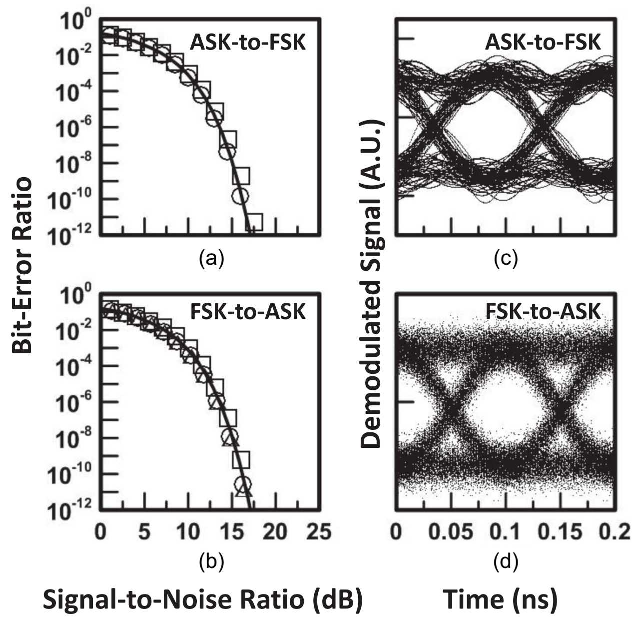

Fig. 6. (a) and (b) BER in terms of SNR. Squares: lower sidebands. Up-triangles: central components. Circles: upper sidebands. BER of the data-modulated incoming optical signal is also shown as solid curves. (c) and (d) Eye diagrams of the upper sideband for BER at 10^{-9}. Note $\xi = 0.35$, $f = 50$ GHz, $m = 0.1$ for ASK, $m = 0.5$ for FSK, and the bit rate is 10 Gb/s.

openings are observed. Similar observations of eye diagrams are also found for other frequency components and other injection conditions under study.

V. Conclusion

Before summarizing our study, a few remarks are made as follows to clarify the scope and analysis in this work from our previous ones briefly addressed in Section I, which also adopt P1 dynamics of semiconductor lasers for different purposes of optical signal processing. First, in our work on optical frequency conversion [34], even though different optical modulation formats of the data were analyzed to address the modulation format transparency of the system, the scope of the work focuses only on conversion between different frequency channels with the same optical modulation format. Conversion between different optical modulation formats using P1 dynamics was not proposed nor addressed at all. Second, in our study of conversion from ASK baseband optical signals to FSK microwave signals [36], even though modulation format conversion was discussed, the scope of the study emphasizes only on conversion from optical ASK to microwave FSK. Conversion from optical ASK to optical FSK and vice versa using P1 dynamics were not demonstrated nor discussed at all. Hence, even though the proposed conversion scheme in the present study results from similar mechanisms and generates similar characteristics, the motivation and scope here are completely different from our previous works. Accordingly, the corresponding analyses and discussions are different in order to address different issues of research or practical interest.

In summary, P1 nonlinear dynamics of semiconductor lasers is proposed for optical modulation format conversion between ASK and FSK. Under proper injection of an incoming optical signal to be format-converted, a semiconductor laser can be driven at P1 dynamics due to the dynamical competition between the injection-imposed laser oscillation and the injection-shifted cavity resonance. The intensity and frequency of each induced spectral component are strongly determined by the intensity and the frequency of the incoming optical signal. Optical modulation format conversion between ASK and FSK can therefore be achieved by applying such a mechanism. The conversion depends solely on the dynamical interaction between the incoming optical signal and the shifted cavity resonance of the injected laser. Therefore, only a typical semiconductor laser is necessary as the key conversion unit. Both ASK-to-FSK and FSK-to-ASK conversions can be achieved using the same system. In addition, simultaneous frequency conversion of the incoming optical carrier is possible. A wide dynamic range of the input modulation index is allowed. Different output modulation indices can be achieved by using different spectral components or different injection conditions.

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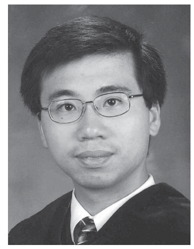

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