Radio-over-Fiber DSB-to-SSB Conversion Using Period-One Dynamics of Semiconductor Lasers

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Abstract

Direct or external modulation scheme typically adopted in radio-over-fiber systems generates optical double-sideband modulation (DSB) signals. However, due to the microwave fading effect, optical single-sideband modulation (SSB) signals are preferred, therefore requiring DSB-to-SSB conversion. In this study, period-one nonlinear dynamics of semiconductor lasers is investigated to conduct such conversion for microwave frequency of more than 100 GHz. Only a typical laser is required and system self-tunability to the adjustment in microwave frequency is feasible.

I. INTRODUCTION

Radio-over-fiber has attracted much attention for wireless access networks, which distributes data-encoded microwave subcarriers over fibers to remote base stations. Direct or external modulation of semiconductor lasers is the simplest scheme to generate microwave subcarriers with high spectral purity. Optical double-sideband (DSB) modulation signals, however, are typically generated, leading to microwave fading over fiber distribution. To minimize the fading effect, optical single-sideband (SSB) modulation signals are preferred. Therefore, various DSB-to-SSB conversion schemes have been proposed [1-3]. In this study, we demonstrate the application of period-one (P1) nonlinear dynamics in semiconductor lasers for such conversion. Figure 1 shows the proposed system consisting of a typical single-mode semiconductor laser. Under continuous-wave (CW) optical injection with proper power and frequency, the laser intensity can exhibit high-frequency single-period oscillation at f_0, which is commonly referred to as P1 nonlinear dynamics. The optical spectrum consists of a regeneration of the injection and two oscillation sidebands equally separated away from the regeneration by f_0 with asymmetric intensity. Such an asymmetric feature is applied in this study for the DSB-to-SSB conversion if the input signal is microwave modulated with a DSB feature.

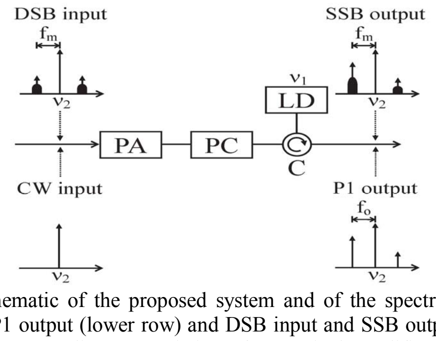

Fig. 1: Schematic of the proposed system and of the spectra for CW input and P1 output (lower row) and DSB input and SSB output (upper row). PA, power adjuster consisting of an optical amplifier or/and an attenuator; PC, polarization controller; C, circulator; LD, laser diode.

II. NUMERICAL MODEL

In this study, investigation is conducted through numerical calculation, and a single-mode model of a semiconductor laser subject to external optical injection is considered [3-5]

$$\frac{da}{dt}=\frac{1}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n}-\gamma_p(2a+a^2)\right](1+a)+F_a$$
$$+\xi_i\gamma_c[1+m(1+s(t)\cos\omega_m t)]\cos(\Omega_i t+\phi) \quad (1)$$

$$\frac{d\phi}{dt}=-\frac{b}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n}-\gamma_p(2a+a^2)\right]+\frac{F_\phi}{1+a}$$
$$-\frac{\xi_i\gamma_c}{1+a}[1+m(1+s(t)\cos\omega_m t)]\sin(\Omega_i t+\phi) \quad (2)$$

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

Here, a is the normalized field amplitude of the injected laser, ϕ is the phase difference between the injection field and the injected laser, and $\tilde{n}$ is the normalized carrier density of the injected laser. The laser intrinsic parameters γ_c, γ_s, γ_n, γ_p, and b are the cavity decay rate, spontaneous carrier decay rate, differential carrier decay rate, nonlinear carrier decay rate, and linewidth enhancement factor, respectively. The normalized, dimensionless bias current parameter $\tilde{J}$ is the ratio between the amount of bias current above the threshold and the threshold bias level of the injected laser. The dimensionless injection parameter ξ_i is proportional to the ratio of the electric fields between the injection signal and the free-running injected laser. The detuning frequency $f_i=\Omega_i/2\pi$ is the frequency offset of the injection field from the free-running frequency of the injected laser. The noise-source parameters, F_a and F_ϕ, are characterized by a spontaneous emission rate. The microwave carried by the injection signal is described in Eqs. (1) and (2), where m is the microwave modulation index, $f_m=\omega_m/2\pi$ the microwave modulation frequency, and *s(t)* the information. A second-order Runge-Kutta method is used to solve Eqs. (1)–(3) together with experimentally measured laser parameters [3-5], where $\tilde{J}=1.222$, $\gamma_c=5.36\times10^{11}\,\mathrm{s}^{-1}$, $\gamma_s=5.96\times10^{9}\,\mathrm{s}^{-1}$, $\gamma_n=7.53\times10^{9}\,\mathrm{s}^{-1}$, $\gamma_p=1.91\times10^{10}\,\mathrm{s}^{-1}$, and $b=3.2$.

III. RESULTS

Figure 2(a) shows the optical spectrum of the injected laser subject to a CW optical input at (ξ_i, f_i) = (0.4, 57 GHz) under the period-one dynamics (blue curve). For comparison, the spectra of the injected laser under free-running (gray curve) and the CW input (red curve) are also shown. A regeneration of the CW input appears due to the injection pulling effect. Equally separated oscillation sidebands from the regeneration by f_0 = 60 GHz also emerge, where the lower sideband is stronger by 35 dB compared to the upper one, resulting from the resonance enhancement of the red-shifted laser cavity caused by the injection [3-5]. Taking advantage of such sideband asymmetry enables the proposed DSB-to-SSB conversion, as Fig. 2(b) shows. Now the input optical signal is microwave-modulated at $f_m = f_0$ = 60 GHz, leading to a DSB feature (red curve) with the optical carrier 26-dB stronger than both modulation sidebands. Under the same (ξ_i, f_i), the injected laser emits a nearly SSB output at exactly f_m (blue curve), where the lower modulation sideband is now stronger by 37 dB compared to the upper one. Figure 3 shows the data quality before and after the conversion (open and closed triangles), where a bit-error ratio (BER) down to 10^{-12} and a clear eye diagram are observed. This shows that the proposed system regenerates microwave features of an optical DSB input while converting its optical feature into SSB. To achieve the conversion of a DSB input at a different f_m, ξ_i and/or f_i can be adjusted for a specific $f_0 = f_m$, up to at least 100 GHz, with a similar SSB output feature.

In fact, the system works even if $f_m \neq f_0$. Under the same (ξ_i, f_i) where f_0 = 60 GHz, Fig. 2(c) shows a similar SSB output with f_m = 64 GHz (blue curve) for a DSB input at f_m = 64 GHz (red curve). This implies that the modulation sidebands lock P1 oscillation sidebands. Similar BER behavior is observed for this operating

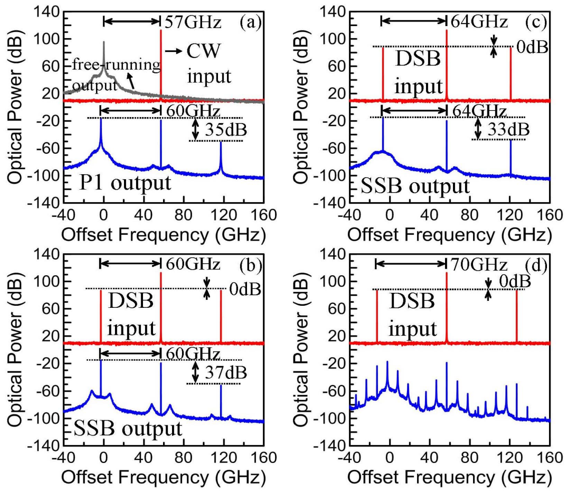

Fig. 2: Optical spectra of CW and DSB inputs (red curves), P1 and SSB outputs (blue curves), and free-running output (gray curve). For visibility, blue curves are shifted down with respect to red curves. X-axes are relative to the free-running frequency of the injected laser.

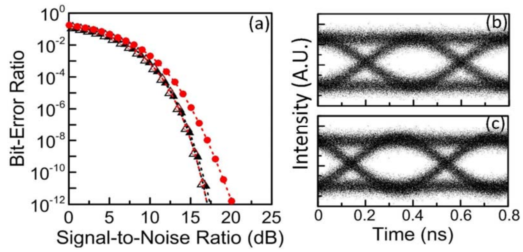

Fig. 3: (a) Bit-error ratio in terms of signal-to-noise ratio. Open and closed triangles for DSB input and SSB output, respectively, at (ξ_i, f_i, f_m) = (0.4, 57 GHz, 60 GHz). Open and closed circles for DSB input and SSB output, respectively, at (ξ_i, f_i, f_m) = (0.4, 57 GHz, 64 GHz). All bit rates are fixed at 2.5 Gb/s. (b)(c) Eye-diagrams for open and closed triangles in (a), respectively, at BER = 10^{-9}.

condition (open and closed circles). The system regenerates the DSB input while converting it with an SSB feature even if f_m varies from 54 to 65 GHz under the present (ξ_i, f_i), showing the system self-tunability to f_m adjustment without the change of the operating condition. As Fig. 2(d) shows, when f_m varies out of this locking range (red curve), unlocking between sidebands produces a nonlinear wave-mixing output (blue curve).

IV. CONCLUSION

Period-one nonlinear dynamics of semiconductor lasers is demonstrated for DSB-to-SSB conversion. The proposed scheme depends solely on the property of input signals for a given laser, and thus only a typical laser is required as the main conversion unit. Conversion can be achieved for an operating microwave frequency of more than 100 GHz. System self-tunability to the adjustment in the operating microwave frequency is feasible. Numerical observations presented in this study have recently been verified by our preliminary experimental work.

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