English

Research Express@NCKU Volume 15 Issue 1 - August 6, 2010
[http://research.ncku.edu.tw/re/articles/e/20100806/2.html]

All-optical frequency conversion using nonlinear dynamics of semiconductor lasers

Sheng-Kwang Hwang[1*], How-Foo Chen[2], and Che-Yang Lin[3]

[1]Department of Electro-Optical Engineering, National Cheng Kung University, Tainan, Taiwan
[2]Institute of Biophotonics, National Yang Ming University, Taipei, Taiwan
[3]Graduate Institute of Opto-Mechatronics, National Chung Cheng University, Chiayi, Taiwan

skhwang@mail.ncku.edu.tw

Optics Letters 34 (6), 812-814 (2009)

There has been much effort devoted to frequency conversion technology due to the strong demand in wavelength-division-multiplexed optical networks [1,2]. A frequency converter converts an incoming optical carrier of one frequency to an outgoing optical carrier of another frequency while preserving the quality of carried data as much as possible. Several schemes have been proposed to achieve frequency conversion. The most straight forward scheme is an electro-optic converter which consists of a photo-detector followed by a laser that re-transmits the incoming optical signal on the new frequency. However, disadvantages of this technique, which include complexity and large power consumption, have directed the interest to the all-optical approach. The latter enables direct translation of the information on the incoming frequency to a new frequency without entering the electrical domain, which is promising since not only the complexity and power consumption of a frequency converter are much reduced but also the flexibility and reconfigurability are greatly improved. However, most proposed methods, such as applying cross gain modulation in semiconductor optical amplifiers, suffer from the need of extra optical beams besides the incoming optical carrier and also suffer from the limited modulation format transparency, making the configuration and operation of such systems complicated and limited.

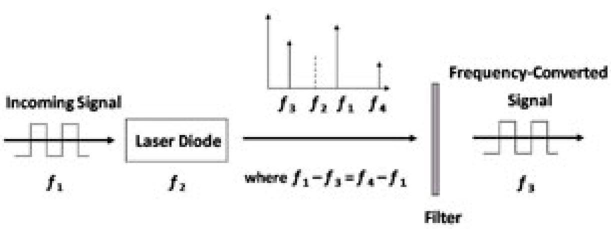

Fig. 1. Schematic configuration of the proposed system.

In this study, we propose to use period-one nonlinear dynamics of semiconductor lasers for all-optical frequency conversion, as shown in Fig. 1. The incoming optical signal at f_1 locks the laser originally oscillating at f_2. The necessary gain for the laser is, however, modified with the introduction of the injection, leading to the change in the carrier density of the laser. This in turns modifies the refractive index of the laser cavity through the antiguidance effect, resulting in the frequency shift of the cavity resonance. Therefore, there exists a dynamical competition between the preferred cavity resonance and the injection-imposed oscillation, which significantly modifies the dynamics of the injected laser. Under proper operating conditions, this would lead to the emergence of frequency components at f_3 and f_4 through Hopf bifurcation, which is a typical signature of the period-one nonlinear dynamics [3,4]. A modulated incoming optical signal varies the carrier density and refractive index of the laser dynamically, thus encoding the data on the emergent components. Through filtering, a frequency-converted optical signal at, for example, f_3 is obtained.

Optical spectra of period-one dynamics under different conditions of injection with no data are shown in Fig. 2. Note that the square of the injection parameter, ξ, is proportional to the injection power actually received by the laser, and the detuning frequency, f, is the frequency offset of the injection from the free-running frequency of the laser. For each injection condition, the laser is locked on to the incoming optical signal, resulting in the spectral component at the injection frequency. The injection modifies the relaxation resonance of the laser, leading to the emergence of sidebands. These sidebands are highly asymmetric in intensity and are equally separated in frequency from the injection. The frequency and intensity of each sideband, however, depend significantly on both the level and frequency of the injection. As shown in Figs. 2(a)-(c), the frequency offset of either sideband from the injection frequency increases from 51 to 54 GHz when ξ is increased from 0.2 to 0.4 while f is fixed. On the other hand, it enhances from 41 to 54 GHz when f is increased from 30 to 50 GHz while ξ is kept constant, as shown in Figs. 2(d)-(f).

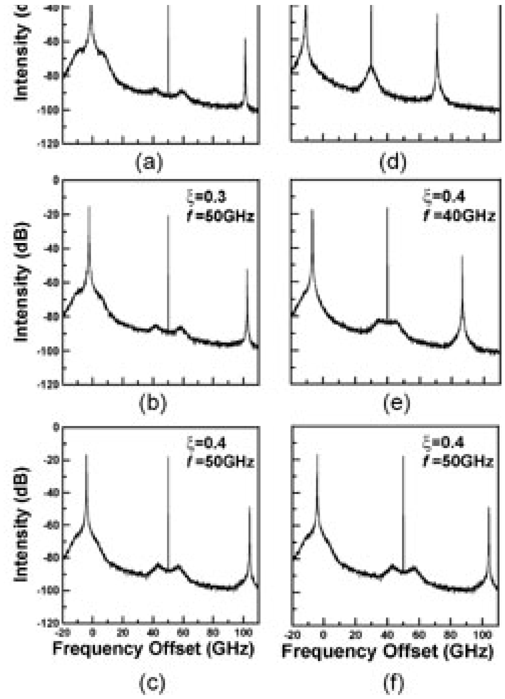

Fig. 2. Optical spectra of period-one dynamics under different injection conditions as marked in each plot. The frequency axis is relative to the free-running frequency of the injected laser.

The frequency shift of the converted optical signal in terms of the injection condition is shown in Fig. 3. Under f = 50 GHz, the frequency shift increases continuously and approximately linearly from about 50 to 54 GHz while ξ is increased from 0.05 to 0.4. A higher frequency shift is feasible if a higher injection level can be achieved practically. A higher frequency shift can also be achieved if f is increased. Under ξ = 0.4, for example, the frequency shift increases continuously and approximately linearly from 41 to 63 GHz when f is adjusted from 30 to 60 GHz. The frequency shift, in fact, can be adjusted from the order of 0.001 THz to the order of 0.1 THz, which is practically limited by the free spectral range of the laser under study [3,5]. It can thus be increased by employing lasers with a short cavity.

The static characteristics of the P1 dynamics in terms of the injection condition shown in Fig. 2 also suggest that a dynamical variation in either the level or the frequency of the incoming optical signal would lead to a dynamical change in both the intensity and frequency of each frequency component. This implies that frequency conversion can be carried out for optical signals with not only amplitude modulation but also frequency modulation and phase modulation. This also suggests that frequency down-, no-, and up-conversion, which are equivalent to the lower sideband, central component, and higher sideband, respectively, can be simultaneously achieved. Figure 4 shows the bit-error ratio in terms of signal-to-noise ratio for the proposed system under ξ = 0.4 and f = 50 GHz with 2.5 Gbits/s modulation. Bit-error ratio down to 10^{-12} can be achieved for all cases under study, which follows closely with that of the corresponding back-to-back case. No error floor is observed, and no or only a slight power penalty is shown, suggesting that the quality of carried data is preserved.

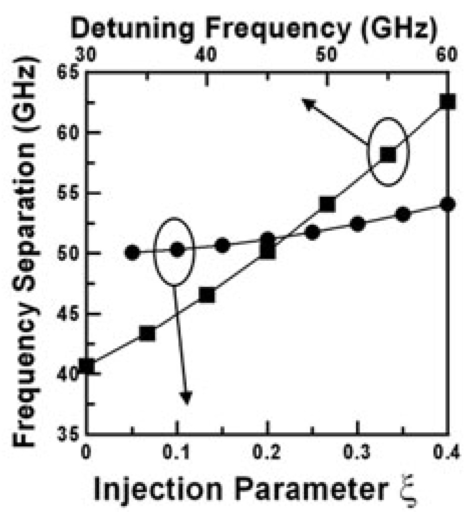

Fig. 3. Frequency shift of the converted optical signal in terms of injection condition. Circles: f = 50 GHz; Squares: ξ = 0.4.

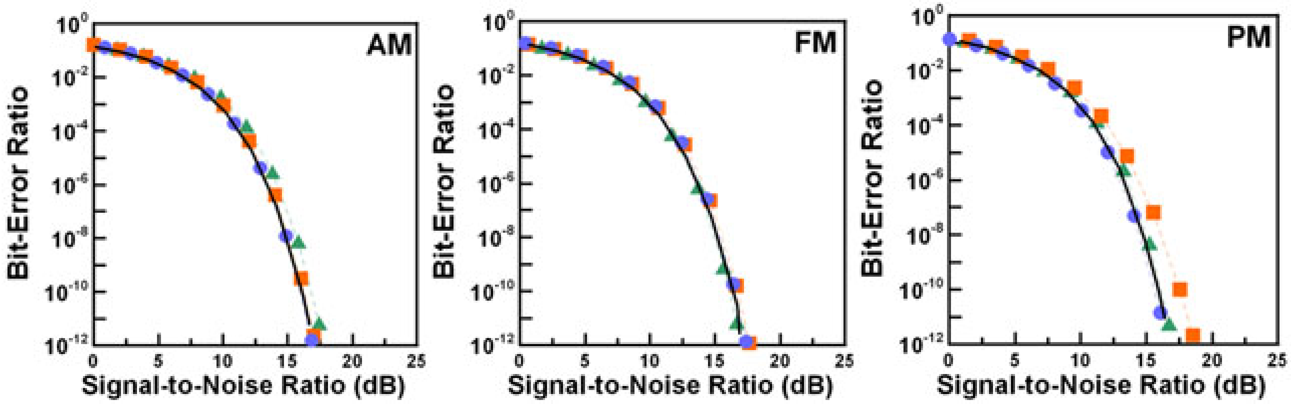

Fig. 4. BER in terms of SNR for frequency down- (squares), no- (circles), and up-conversion (triangles) under AM, FM, and PM, respectively, at $\xi = 0.4$ and $f = 50$ GHz with 2.5 Gbits/s modulation. BER of the data-modulated incoming optical signal is also shown as the solid curve in each plot.

In conclusion, nonlinear dynamics of semiconductor lasers is proposed and investigated for all-optical frequency conversion. When a semiconductor laser is subject to an incoming optical signal, it can enter into period-one nonlinear dynamics through Hopf bifurcation. By taking advantage of the dynamics, tens to hundreds of gigahertz of frequency conversion can be achieved, which can be continuously and dynamically tuned over a broad range by controlling the injection level and frequency. No probe or pump beam is necessary as in many other systems, which would greatly simplify the structure of the conversion system. BER down to 10^{-12} is observed with no or a slight power penalty for different modulation formats, offering the capability of modulation format transparency. Frequency down-, no-, and up-conversion can be simultaneously achieved and individually selected, increasing the flexibility and re-configurability of the system. The results presented here not only demonstrate the feasibility of using nonlinear semiconductor laser dynamics for all-optical frequency conversion, but also suggest that a simple nonlinear dynamical system can carry out multiple functionalities simultaneously which can be used to simplify or even replace the complex systems built upon the philosophy of linear dynamics.

References:

[1] T. Durhuus, B. Mikkelsen, C. Joergensen, S.L. Danielsen, and K.E. Sturbkajer, ”All-optical wavelength conversion by semiconductor optical amplifiers,” J. Lightwave Technology **14**, 942-954 (1996).
[2] S.J.B. Yoo, “Wavelength conversion technologies for WDM network applications,” J. Lightwave Technology, **14**, 955-966 (1996).
[3] S. K. Hwang, J. M. Liu, and J. K. White, “Characteristics of period-one oscillations in semiconductor lasers subject to optical injection,” IEEE J. Sel. Top. Quantum Electron. **10**, 974–981 (2004).
[4] S.K. Hwang and D.H. Liang, “Effects of linewidth enhancement factor on period-one oscillations of optically injected semiconductor lasers,” Appl. Phys. Lett. **89**, 061120 (2006).
[5] S.C. Chan, S.K. Hwang, and J.M. Liu, “Radio-over-fiber AM-to-FM upconversion using an optically injected semiconductor laser,” Opt. Lett. **31**, 2254 (2006).