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Period-One Nonlinear Dynamics of Semiconductor Lasers for Photonic Microwave Mixing

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Abstract–Photonic microwave mixing has been considered a key functionality in radio-over-fiber systems adopting high microwave subcarrier frequencies for antenna remoting applications. Such a functionality enables microwave subcarrier frequency upconversion for wireless transmission in downlinks or downconversion for photodetection in uplinks through photonic approaches. In this study, an approach is proposed by taking advantage of the nonlinear wave mixing inside a semiconductor laser between an input optical signal carrying a microwave subcarrier and the period-one nonlinear dynamics invoked by the input optical signal.

1. Introduction

Period-one (P1) nonlinear dynamics in a semiconductor laser subject to continuous-wave (CW) optical injection have attracted much research interest not only for fundamental understandings of nonlinear dynamics and laser physics [1-7] but also for various technological applications in photonics and microwaves [8-24]. For example, by taking advantage of the self-sustained microwave oscillation of the laser intensity, the P1 dynamics have been proposed for photonic microwave generation [8-10, 12, 15, 16, 19-21, 24, 25]. While broadband frequency tunability can be achieved by simply adjusting the power and frequency of the optical injection, optical single-sideband modulation is so feasible as to mitigate microwave power fading over fiber distribution. In addition, by taking advantage of the multiple spectral components induced by the optical injection, the P1 dynamics have been proposed for optical frequency conversion [13]. While optical frequency down-, no-, and up-conversion can be simultaneously or individually achieved, the data modulation format, either amplitude modulation (AM), frequency modulation (FM), or phase modulation, can be maintained after conversion. Moreover, since the intensity and frequency of each spectral component depend on the injection level and frequency, the P1 dynamics have also been demonstrated for modulation format conversion between optical AM and optical FM [18] and from optical AM to microwave FM [11]. While different output modulation indices can be achieved by using different spectral components or different injection conditions, simultaneous optical frequency conversion is also possible. In addition, by adopting the intensity asymmetry between the oscillation sidebands, the P1 dynamics have been investigated for conversion from optical double-sideband modulation to optical single-sideband modulation [22]. Self-adaptation to changes in the operating microwave frequency is feasible, and stable operation under fluctuations of the injection level and frequency is achievable. Furthermore, the P1 dynamics have also been studied for photonic microwave amplification [23] by applying the red-shifted cavity resonance enhancement. The amplification can be achieved for a broad microwave range, up to at least 60 GHz, and for a wide gain range, up to at least 30 dB.

In this study, an approach is proposed for highly efficient photonic microwave mixing by taking advantage of the nonlinear wave mixing occurred inside a semiconductor laser between a microwave-modulated (MM) optical input and the P1 dynamics of the semiconductor laser invoked by the MM optical input. Photonic microwave mixing has been considered a key functionality in radio-over-fiber systems adopting high microwave subcarrier frequencies for antenna remoting applications, such as broadband wireless networks and electronic warfare systems. Such a functionality enables microwave subcarrier frequency upconversion or downconversion. Photonic approaches based on, for example, optical intensity modulators, optical phase modulators, and semiconductor optical amplifiers [26-32] provide various promising advantages, including broadband frequency tunability for either upconversion or downconversion, infinite isolation between microwave subcarriers and microwave local oscillators, and immunity to electromagnetic interference, which are difficult to achieve using electronic approaches. However, these photonic approaches typically suffer from significant power conversion loss of microwave subcarriers, require substantial power of electronic microwave local oscillators, experience considerable power loss of optical inputs, and need high-speed capability of photonic and/or electronic devices. The approach proposed in this study highly improves these performance characteristics and operating requirements.

2. Experimental Setup

Figure 1 presents a schematic of the experimental setup.

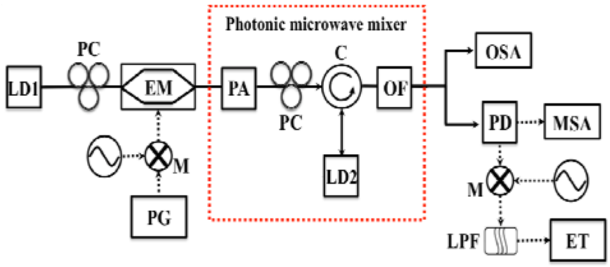

Fig. 1. Schematic of the experimental setup. LD1, laser diode 1; PC, polarization controller; EM, external modulator; M, mixer; PG, pattern generator; PA, power adjuster; C, circulator; LD2, laser diode 2; OF, optical bandpass filter; OSA, optical spectrum analyzer; PD, photodiode; MSA, microwave spectrum analyzer; LPF, electrical low-pass filter; ET, error tester.

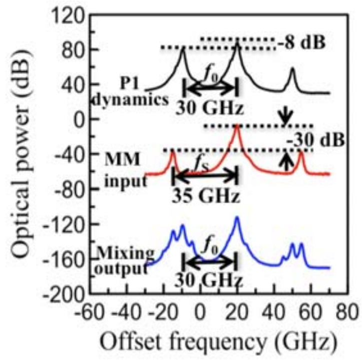

Fig. 2. Optical spectra of the P1 dynamics (gray curve), the MM input (red curve), and the wave mixing (blue curve) at (ξ_i, f_i) = (1.01, 20 GHz). The x axes are relative to the free-running frequency of LD2.

The proposed photonic microwave mixing system consists of a single-mode distributed-feedback semiconductor laser (Gooch & Housego AA0702), LD2. Under a bias current of 33 mA and a stabilized temperature of 25.6º C, the free-running LD2 oscillates at 193.345 THz with an optical power of 4.9 mW and a relaxation resonance frequency of about 10 GHz. An input optical carrier is generated by another single-mode distributed feedback semiconductor laser of a similar type, LD1, and is directed toward LD2 through a circulator. To excite the P1 dynamics, the frequency of the input optical carrier is detuned by f_i from the free-running frequency of LD2 through adjusting the temperature or bias current of LD1. In addition, the power of the input optical carrier is varied using a power adjuster consisting of an attenuator and/or an amplifier, and is measured at the output port of the circulator connected to the slave laser. To indicate the injection strength received by LD2, an injection ratio ξ_i, defined as the square root of the power ratio between the input optical carrier and the free-running LD2, is used. A polarization controller aligns the polarization of the input optical carrier with that of LD2 to maximize the injection efficiency. An external modulator (EOspace AX-AV5-40) superimposes a microwave subcarrier at a frequency f_m from a microwave source (Agilent E8257D) on the input optical carrier. Data from a pattern generator (Anritsu MP2101A) are added onto the microwave subcarrier through an electronic microwave mixer. The output of LD2 is sent through a tunable optical bandpass filter (Alnair Labs BVF-200CL) to select the spectral components of interest before entering an optical spectrum analyzer (Advantest Q8384) and a microwave spectrum analyzer (Agilent N9030A PXA) following a 50-GHz photodiode (u2t Photonics XPDV2120R). For the bit-error ratio (BER) analysis, the photodetected signal is first downconverted to the baseband and next sent through an electrical low-pass filter before entering an error tester (Anritsu MP2101A).

3. Results and Analyses

To gain understanding of why the proposed mixing approach can perform as indicated above, let us first study the spectral features of a P1 dynamical state when LD2 is subject to a CW optical input at (ξ_i, f_i) = (1.01, 20 GHz), shown as the black curve in Fig. 2. Not only the CW optical input regenerates at the offset frequency of 20 GHz, but also oscillation sidebands equally separated from the regeneration by f_0 = 30 GHz sharply emerge. This characteristic of self-sustained microwave oscillation suggests that an optically injected laser at the P1 dynamics can work by itself as a microwave local oscillator, a photonic yet all-optical one, for photonic microwave mixing. In addition, f_0 is not limited by the laser intrinsic response and, in fact, can be broadly tuned from a few gigahertz to tens or even hundreds of gigahertz by simply adjusting (ξ_i, f_i) [20, 22, 23]. Hence, as opposed to most other mixing approaches, no electronic microwave local oscillator is required, thus reducing system power consumption, and no high-speed photonic device, the laser here, is needed, thus relaxing high-frequency capability requirements. Note that, owing to the laser intrinsic noise, the microwave stability of the P1 dynamics is typically poor, on the order of 1 to 10 MHz [24, 25]. To demonstrate the best possible performance characteristics of the proposed mixing approach, a microwave stabilization scheme based on double locking [8] is adopted in this study, not shown in Fig. 1.

To demonstrate microwave mixing, an MM optical input at f_m = 35 GHz, as the red curve in Fig. 2 shows, with the optical carrier 30-dB stronger than both modulation sidebands, corresponding to an optical modulation depth of about 6%, is injected into LD2 at the same (ξ_i, f_i) = (1,01, 20 GHz). As the blue curve in Fig. 2 presents, not only the MM optical input regenerates itself, including the optical carrier and both modulation sidebands, but also the optical carrier excites a P1 dynamical state at f_0 = 30 GHz with key features closely similar to the one as the black curve shows. Since both modulation sidebands are too weak to frequency-lock the oscillation sidebands, nonlinear wave mixing between the excited P1 dynamical state and the regenerated MM optical input happens inside LD2 [22]. By selecting the

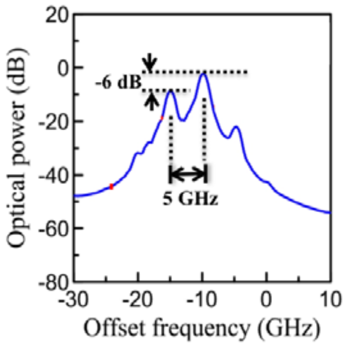

Fig. 3. Optical spectrum of the wave mixing in Fig. 2 after optical filtering. The x axes are relative to the free-running frequency of LD2.

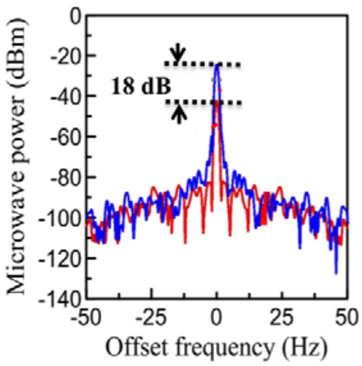

Fig. 4. Microwave spectra of the microwave input (red curve) and output (blue curve), centering at 35 and 5 GHz, respectively.

excited lower oscillation sideband and the regenerated lower modulation sideband using the tunable optical bandpass filter, as shown in Fig. 3, an optical output with two dominant tones is obtained, which are separated by $f_m - f_0$ = 5 GHz and which are 6-dB different in power, suggesting an improvement of the optical modulation depth as compared with that of the MM optical input. After photodetection, as Fig. 4 presents, this optical output results in a downconverted microwave subcarrier at 5 GHz with power amplification of 18 dB, suggesting a conversion gain, and with a 3-dB microwave linewidth of less than 1 Hz, the same as the input microwave subcarrier.

Figure 5 presents the BER analysis at a data rate of 1.25 Gb/s. The BER behavior of the downconverted microwave subcarrier is similar to that of its corresponding input microwave subcarrier, where a BER down to 10^{-9} is achieved. Owing to the conversion gain, a sensitivity improvement of about 9 is achieved, which is about one half of the conversion gain shown in Fig. 4. These results suggest that the quality of the data is mostly preserved after conversion.

4. Conclusion

This study investigates photonic microwave mixing by taking advantage of the nonlinear wave mixing occurred

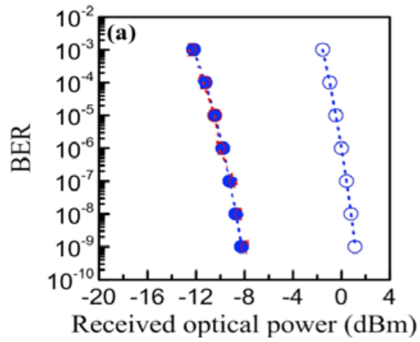

Fig. 5. BER in terms of the received optical power for frequency downconversion from 35 GHz (open symbols) to 5 GHz (closed symbols).

inside a semiconductor laser between a microwave modulated optical input and the P1 dynamics of the semiconductor laser invoked by the optical input. The laser works not only as a photonic microwave mixer but also as a photonic microwave local oscillator. Hence, no electronic microwave local oscillator is required and no high-speed semiconductor laser is needed. Owing to the improvement of the optical modulation depth after conversion, a conversion gain of 18 dB is achieved. The microwave phase quality, such as linewidth, is mainly preserved after conversion. A BER down to 10^{-9} at 1.25 Gb/s with a detection sensitivity improvement of 9 dB is achieved.

Acknowledgments

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