

OPTICALLY INJECTED SEMICONDUCTOR LASER FOR PHOTONIC MICROWAVE FREQUENCY MIXING IN RADIO-OVER-FIBER

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Abstract—Nonlinear dynamics of an optically injected semiconductor laser for microwave frequency mixing are experimentally investigated. Through optical injection, the laser is driven into the nonlinear period-one (P1) dynamical state and acts as a broadly tunable photonic microwave oscillator. With an external current modulation at an intermediate frequency, the P1 oscillation is modulated accordingly, thus achieving frequency up-conversion beyond the laser bandwidth. Using a 2.5-Gbps-grade laser, binary phase-shift keying (BPSK) data signal is up-converted from an intermediate frequency of 2 GHz to a subcarrier frequency as high as 20 GHz. While the direct modulation bandwidth limits the intermediate frequency, it does not limit the subcarrier frequency. The approach uses only low-cost lasers and requires no high-speed electronic mixers.

1. INTRODUCTION

Nonlinear dynamics of semiconductor lasers invoked by optical injection have been investigated for various applications in the last decade [1–5]. Among the applications is the radio-over-fiber (RoF) system in which radio or wireless signals on a microwave subcarrier are transmitted through an optical carrier over optical fibers. Sharing the intrinsic merits of optical fibers, RoF systems have the advantages such as reduced size, weight, and cost, low attenuation, immunity to electromagnetic interference, low dispersion, and high data transfer capacity [6, 7]. The original data to be transmitted from the central office is generally at the baseband or an intermediate frequency. It has to be up-converted to the microwave subcarrier frequency for downlink

transmission. In order to reduce the cost on high-speed electronics, it is desired that microwave generation and frequency up-conversion are performed optically at the central office.

Various approaches of such optical microwave frequency mixing have been investigated. The nonlinearities of a semiconductor optical amplifier (SOA) [8], a highly nonlinear fiber (HNLF) [9], and a base station electronic mixer [10] were considered. However, all these methods required high-speed external modulators that are generally expensive and lossy. As an alternative, a technique based on modulating a mode-locked multisection laser was reported [11]. The approach employed no external modulators, but the tunability of the subcarrier frequency was inherently limited by the laser structure, which required sophisticated cavity design. Recently, the nonlinear response of a vertical-cavity surface-emitting laser (VCSEL) biased close to threshold was utilized [12]. While the approach was relatively simple, the subcarrier frequency was limited by the intrinsic direct modulation bandwidth to only 3.1 GHz.

The nonlinear dynamical period-one (P1) oscillation of optically injected semiconductor lasers offers a solution [1]. Through optical injection of proper power and detuning frequency, P1 oscillation can be invoked through undamping the relaxation oscillation. Photonic microwave is generated even without direct modulation of the bias current. The bandwidth limitation imposed by the direct modulation response can be circumvented, where tunable generation of microwave frequencies six-fold beyond the relaxation oscillation frequency has been investigated [3]. For example, stable subcarrier frequency of 40 GHz has been experimentally obtained [13]. The P1 oscillation has been investigated for both RoF downlink and uplink data transmissions [2, 5]. However, these methods required first electrically mixing data to the subcarrier frequency before modulating the lasers. To the best of our knowledge, incorporation of frequency up-conversion using the P1 oscillation for RoF applications has not been investigated.

In this Letter, an ordinary 2.5-Gbps-grade 1.55- μm single-mode distributed feedback (DFB) laser is applied for all-optical microwave frequency up-conversion. Under proper optical injection, the laser is forced into P1 oscillation and experiences intensity oscillation at a characteristic frequency f_0 , which is tuned to 18 GHz for illustration. A data stream in binary phase-shift keying (BPSK) at an intermediate frequency $f_{\text{IF}} = 2$ GHz then modulates the laser directly. The P1 oscillation at f_0 is modulated by f_{IF} accordingly. Data is up-converted to both the upper sideband (USB) at $f_0 + f_{\text{IF}} = 20$ GHz and the lower sideband (LSB) at $f_0 - f_{\text{IF}} = 16$ GHz. Although the subcarriers $f_0 \pm f_{\text{IF}}$ are already significantly greater than the original laser bandwidth, they

can be easily increased by increasing the optical injection strength or detuning frequency. The construction of the central office uses no high-speed electronic mixers. Up-conversion to the subcarrier frequency is performed by the laser without being limited by the direct modulation bandwidth.

The experimental approach in this work is demonstrated for the first time and is consistent with previous numerical simulations, which were based on the well established rate-equation model of optically injected semiconductor lasers [14].

2. EXPERIMENTAL SETUP

2.1. Central Office

The schematic of the experimental setup is shown in Fig. 1. Both the master laser and the slave laser are single-mode DFB lasers of the same model (Mitsubishi ML920T43S-01). The lasers emit at around $1.55\ \mu\text{m}$ and have been designed with electrical bandwidth supporting only up to 2.5 Gbps. At the central office, light from the master laser is injected into the slave laser. The combination of the half-wave plates, the Faraday rotator, and the polarizing beam splitter forms an optical

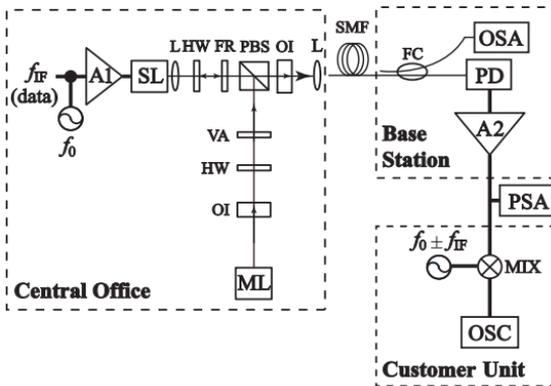


Figure 1. Schematic of the optical injection system for mixing f_0 and f_{IF} for an RoF downlink. ML: Master laser; SL: Slave laser; L: Lens; HW: Half-wave plate; FR: Faraday rotator; PBS: Polarizing beam splitter; VA: Variable attenuator; CIR: Optical circulator; OI: Optical isolator; SMF: Single-mode fiber; FC: Fiber coupler; PD: Photodetector; A1, A2: Electrical amplifiers; PSA: Power spectrum analyzer; OSA: Optical spectrum analyzer. MIX: Electronic mixer; OSC: Oscilloscope. Thin lines: Optical paths. Thick lines: Electrical cables.

circulator which ensures unidirectional optical injection. While the master laser can be any tunable single-mode laser, our experiment employed the laser of the same model as the slave laser to ensure the wavelengths are nearly matched. Nonetheless, fabrication variation of the lasers causes a slight difference in their wavelengths. Thus, both lasers are temperature stabilized so that their free-running wavelengths can be temperature-tuned.

Different dynamics can be invoked in the slave laser through optical injection by varying the injection conditions, including the injection power P_i and the injection detuning frequency f_i , which is defined as the optical frequency difference between the master laser and the free-running slave laser. When the injection forces the slave laser into the nonlinear P1 dynamical oscillation, its output intensity oscillates at a microwave frequency f_0 , even without any current modulation [1]. Tuning of f_0 is achieved through varying P_i and f_i . The injection power P_i is controlled at the variable attenuator, while the injection detuning frequency f_i is controlled by the bias current and the temperatures of the lasers.

2.2. Base Station

The output of the slave laser is transmitted over a 4-km optical fiber to the base station. The optical signal is separated into two branches. One is monitored by an optical spectrum analyzer (HP 86142A). The other branch is detected by a photodetector (Newport AD-10ir), amplified by 40 dB electrically using two microwave amplifiers (HP 83006A and HP 83017A), and monitored by a power spectrum analyzer (Agilent N9010A). As an option, a current modulation at f_0 can be applied to the slave laser to stabilize the P1 oscillation frequency [1], but it is not essential for the frequency mixing described below.

In order to perform all-optical microwave frequency mixing, a current modulation at an intermediate frequency f_{IF} is applied to the slave laser through a 20-dB amplifier (HP 83006A). The P1 oscillation at f_0 is modulated accordingly, generating mixing products at $f_0 \pm f_{IF}$ as subcarrier frequencies for RoF. When f_{IF} carries data from a pattern generator (Agilent N4906B), the data is up-converted to the subcarriers for transmission to the customer unit.

2.3. Customer Unit

The customer unit receives the downlink signal at the subcarriers $f_0 \pm f_{IF}$. For illustration, our experiment simply uses a local oscillator (HP 83630B) at $f_0 + f_{IF}$ or $f_0 - f_{IF}$ to electrically mix with the downlink signal. The local oscillator gives 18-dBm and the conversion loss is

8 dB. The demodulated data is sent to a real-time digital oscilloscope (DSO90254A) of 200 MHz effective bandwidth for observation.

3. EXPERIMENTAL RESULTS

3.1. P1 Oscillation

The master laser is biased at 133.9 mA and temperature stabilized at 18.00 °C; while the slave laser is biased at 40.0 mA and temperature stabilized at 27.00 °C. The threshold of the slave laser is 8.0 mA. Under this operating condition, the slave laser emits 8.17 mW when it is not under optical injection. The master laser is positively detuned from the slave laser with an injection detuning frequency of $f_i = 5$ GHz. When the injection power is adjusted to $P_i = 5.25$ mW, P1 oscillation at $f_0 = 18$ GHz is generated. Fig. 2 shows the optical spectrum centered at the free-running frequency of the slave laser at 193.745 THz. Due to optical injection, a regenerative component at f_i above the free-running frequency is observed, as indicated by the arrow. The nonlinear dynamical P1 oscillation generates the sidebands equally separated by f_0 . A beat signal is thus obtained as a peak at f_0 in the power spectrum in Fig. 3(a). The microwave oscillation is obtained through the nonlinear dynamics alone without applying any current modulation. By fixing the injection detuning frequency at $f_i = 5$ GHz, the generated microwave can be tuned from 12 GHz to 21 GHz by varying the injection power P_i from 1.11 mW to 9.37 mW, as Fig. 3(b) shows. The P1 oscillation frequency f_0 increases nearly linearly with $\sqrt{P_i}$ [15].

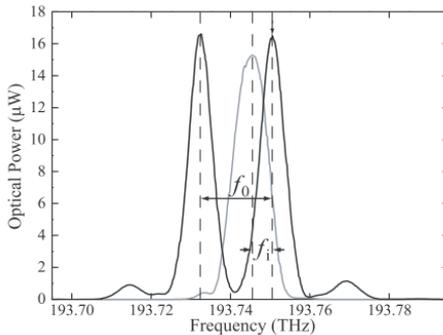


Figure 2. Optical spectrum of the emission from the slave laser under no current modulation. The gray curve is obtained without optical injection. The black curve is obtained with optical injection of $f_i = 5$ GHz and $P_i = 5.25$ mW. The slave laser exhibits P1 oscillation of $f_0 = 18$ GHz. (Resolution bandwidth = 7.5 GHz).

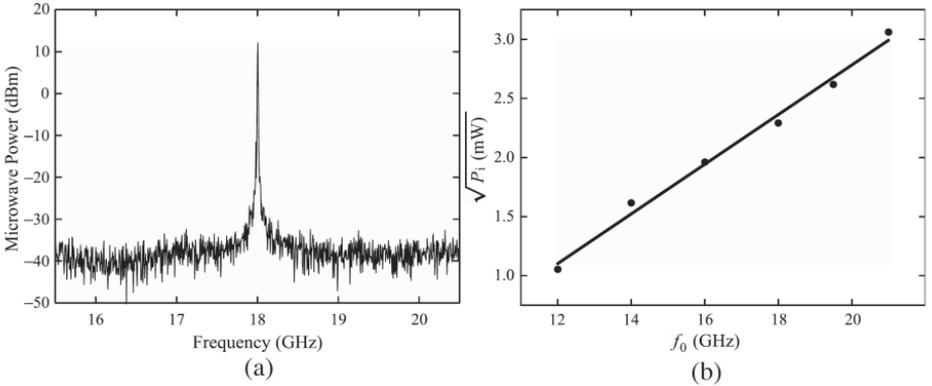


Figure 3. (a) Power spectrum of the slave laser under P1 oscillation at $f_0 = 18$ GHz. No current modulation is applied. (b) Tunability of f_0 by varying P_1 under constant $f_i = 5$ GHz.

It is worth noting that, due to imperfections in optical alignment, only a small portion of the optical injection power actually couples into the slave laser. While it is difficult to directly measure the actual injection power ratio, the experimental results in Fig. 3(b) can be compared to numerical simulation results to deduce the injection power ratio. Using the well established rate equations of intracavity optical field and charge carrier density, together with the experimentally obtained laser dynamical parameters, the P1 oscillation frequency f_0 can be obtained as a function of the injection power ratio [3]. From such approach, the injection power ratio is estimated to be about 1% for Fig. 3(a). The ratio is small because of the experimental challenges in injecting light into the output facets of the slave laser, which typically has only a few micrometers in height and width.

In Fig. 3, while spontaneous emission noise and intrinsic fluctuation of the system lead to a microwave linewidth on the order of 10 MHz, it can be narrowed by a weak current modulation of 5 dBm at f_0 [1]. The modulation remains on for the following characterization of frequency mixing, up-conversion bandwidth, up-conversion power, and data transmission.

3.2. Frequency Mixing

For frequency up-conversion, f_0 is kept at 18 GHz and an additional current modulation at the intermediate frequency $f_{IF} = 2$ GHz and power $P_{IF} = -4$ dBm is applied to the slave laser. Fig. 4 shows that the P1 oscillation is modulated accordingly. Up-converted signals at both $f_0 + f_{IF} = 20$ GHz and $f_0 - f_{IF} = 16$ GHz are clearly identified.

While the USB is slightly stronger than the LSB in the present P1 state, the LSB can become stronger than the USB when a different P1 state is used.

The up-conversion bandwidth of the photonic microwave mixer is characterized by varying f_{IF} , where the optical injection conditions remain constant and P_{IF} is kept constant at -4 dBm. Fig. 5(a) shows the microwave powers at the USB and the LSB as solid and

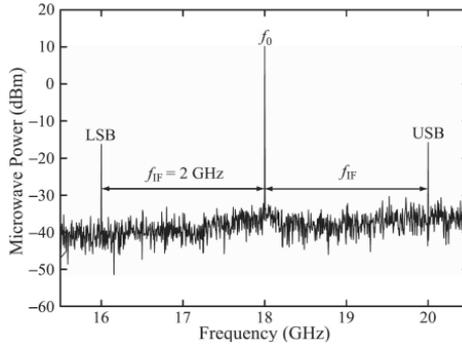


Figure 4. Power spectrum of the slave laser under P1 oscillation at $f_0 = 18$ GHz and current modulation at $f_{IF} = 2$ GHz. The input current modulation power is $P_{IF} = -4$ dBm. Frequency up-conversion from f_{IF} to $f_0 \pm f_{IF}$ is observed.

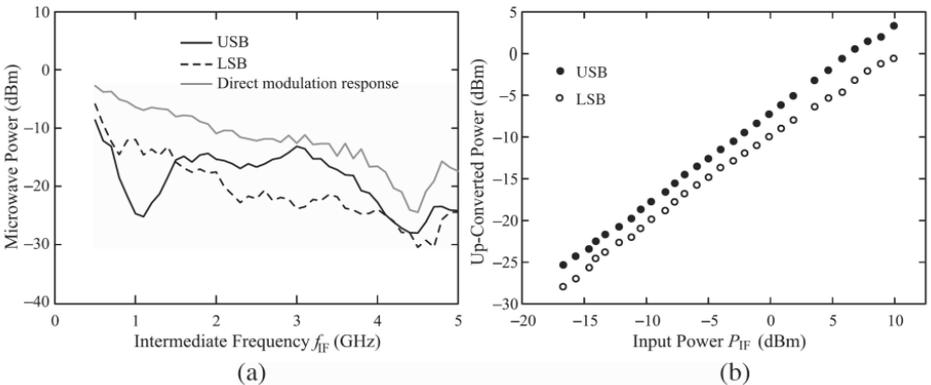


Figure 5. (a) Up-conversion power from the photonic microwave mixing of f_{IF} and $f_0 = 18$ GHz. The solid and dashed dark curves correspond to the USB and the LSB, respectively. For comparison, the gray curve is the direct modulation response of the slave laser. Modulation power is kept at $P_{IF} = -4$ dBm. (b) The USB and LSB power versus P_{IF} at $f_{IF} = 2$ GHz.

dashed dark curves, respectively. The gray curve shows the direct modulation response of the slave laser for comparison. The up-conversion responses roughly follow the trend of the direct modulation response. This indicates that the intermediate frequency f_{IF} is limited by the modulation bandwidth of the slave laser, even though the P1 frequency f_0 is not.

Due to the antiguidance effect associated with a positive linewidth enhancement factor, the optical spectrum of P1 oscillation is generally asymmetric [16–18]. Likewise, asymmetry in the power levels of the USB and LSB is always observed in the mixing experiments. Details require thorough numerical simulation and is beyond the current scope. Nevertheless, such asymmetry was also observed in a related simulation study [14]. Furthermore, as shown in the inset of Fig. 5, the signal powers at both subcarriers increase approximately linearly with P_{IF} . For a noise floor of -30 dBm, there is a linear operational range of more than 20 dB for both the USB and the LSB. Both sidebands are applied as the subcarriers in the following demonstration of data up-conversion.

3.3. Data Up-Conversion

The proposed photonic microwave mixer is further explored for data up-conversion. When BPSK data is modulated on f_{IF} , it is up-converted to the subcarrier frequencies $f_0 \pm f_{IF}$ accordingly. The power spectrum with up-converted 155-Mbps data using $f_0 = 18$ GHz and $f_{IF} = 2$ GHz is shown in Fig. 6(a). Data sidebands are clearly

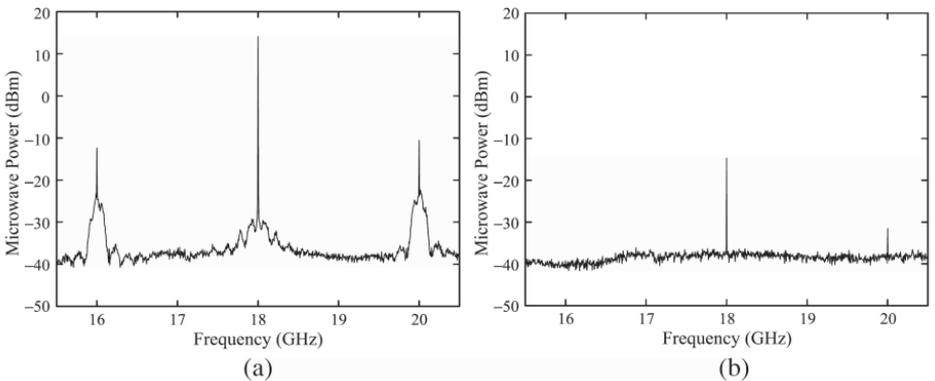


Figure 6. Power spectrum of the slave laser under current modulation at $f_0 = 18$ GHz and $f_{IF} = 2$ GHz. The modulation at f_{IF} carries BPSK data at 155 Mbps. (a) Up-converted signal when optical injection is applied. (b) Up-converted signal when optical injection is removed.

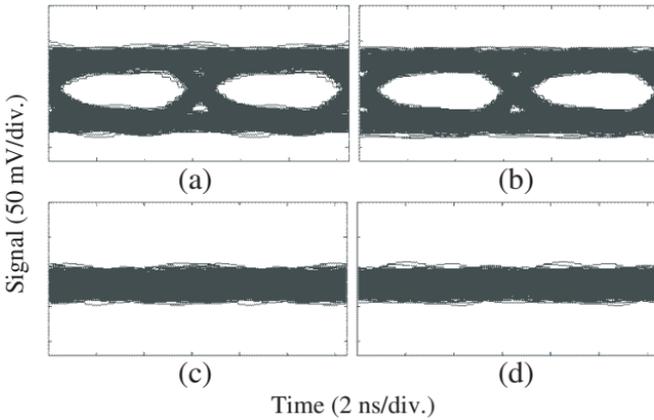


Figure 7. Eye diagrams of the data recovered at (a) 16-GHz LSB with optical injection. (b) 20-GHz USB with optical injection. (c) 16-GHz LSB without optical injection. (d) 20-GHz USB without optical injection.

identified at both the USB and the LSB. The up-converted signals can be radiated to wireless customer units in real applications, although they are sent directly to the customer unit here for illustration. The customer unit directly demodulates the signals by electrically mixing them with a local oscillator at $f_0 \pm f_{IF}$. Data is recovered with bit-error rates (BERs) of 8.02×10^{-11} at the USB and 8.11×10^{-10} at the LSB. The corresponding eye diagrams are shown in Figs. 7(a) and (b). By contrast, no evidence of data up-conversion is identified in the power spectrum in Fig. 6(b) when no optical injection is applied. Any effort to realize data recovery is in vain as the corresponding eye diagrams are completely closed, as shown in Figs. 7(c) and (d). Therefore, optical injection is essential to generating the P1 oscillation as well as performing frequency mixing.

In order to show the system tunability, measurements are made at $(f_0, f_{IF}) = (18 \text{ GHz}, 2 \text{ GHz})$, $(18 \text{ GHz}, 2.3 \text{ GHz})$, and $(16 \text{ GHz}, 2 \text{ GHz})$, where f_0 is tuned by varying the injection conditions. The quality of data up-conversion is quantified by finding the BER. When there is no optical injection, the BER remains on the order of 10^{-1} as no effective data up-conversion is realized. For the proposed system with optical injection, the BER decreases as the received optical power increases, as Fig. 8 shows. For $(f_0, f_{IF}) = (18 \text{ GHz}, 2 \text{ GHz})$, it is observed that the USB has a lower BER than the LSB. This is expected from Fig. 4 as the power of USB is stronger. At a received optical power level of around -2.44 dBm , data up-conversion with BER of less than 10^{-9} can always be achieved for all the settings in Fig. 8.

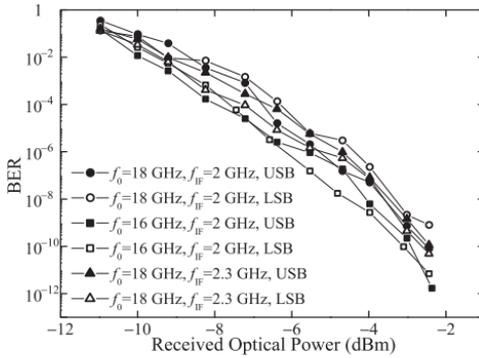


Figure 8. BER of the system under different P1 oscillation frequencies f_0 and intermediate frequencies f_{IF} . Data rate = 155 Mbps.

4. CONCLUSION

An optically injected semiconductor laser in the P1 oscillation state is applied for photonic microwave frequency mixing. The direct modulation bandwidth limits only the intermediate frequency, but not the subcarrier frequency. With an ordinary 2.5-Gbps-grade laser, RoF downlink BPSK signals are up-converted from 2 GHz to a subcarrier frequency of 20 GHz. The system at the central office requires no high-speed lasers, electronic mixers, or external modulators.

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