Double-locked semiconductor laser for radio-over-fiber uplink transmission

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The nonlinear dynamics of an optically injected semiconductor laser are explored for radio-over-fiber uplink transmission. Under optical injection locking, the laser at the base station is operated in the period-one oscillation state, where its intensity oscillates at a tunable microwave frequency. When the oscillation is tuned to the subcarrier frequency, it is further locked by the uplink microwave signal. By simply using an ordinary 2.5-Gbps-grade semiconductor laser, uplink transmission of the phase-shift keying (PSK) signal at a subcarrier of 16 GHz with bit-error rate of less than 10^{-11} is demonstrated experimentally. Microwave PSK to optical PSK is achieved at the double-locked laser, which allows all-optical demodulation without any high-speed microwave electronics. © 2009 Optical Society of America

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Nonlinear dynamics of optically injected semiconductor lasers have recently been applied in radio-over-fiber (RoF) systems. Microwave signals generated by the dynamics have been investigated for downstream RoF transmission [1–4]. Optically injected semiconductor lasers have also been studied as photonic microwave mixers for downlink transmission [5]. In an RoF system, microwave subcarriers are modulated on an optical carrier for transmission through optical fibers between the central office and base stations. Compared with conventional wireless systems, RoF system has the advantages of centralizing high-speed electronics in the central office, low attenuation, large bandwidth offered by the optical fiber, immunity to radio frequency interference, and increased coverage and cell density.

Several approaches have been reported for RoF uplink transmission from the base station to the central office. One relies on using multisection semiconductor lasers at the base stations as millimeter-wave optical transmitters [6]. However, the lasers required special designs that limited the tunability of the frequency. Another approach was based on reusing the downstream wavelength for upstream transmission, which required complicated base station architecture with electrical demodulation and baseband optical modulation [7,8]. As the subcarrier frequency increases beyond a few gigahertz, the need for expensive high-speed electronics becomes an obstacle. Thus, it is desirable to process signals in the optical domain. Such an approach has been reported at 10 GHz using a high-speed external modulator [9].

In this Letter, we demonstrate uplink transmission using a double-locked [1,2] semiconductor laser under nonlinear dynamical period-one (P1) oscillation. When a semiconductor laser is subject to proper optical injection, its nonlinear dynamical P1 oscillation state can be invoked through undamping its relaxation oscillation. Furthermore, as it receives the uplink microwave signal as current modulation, the signal is modulated onto the P1 oscillation. Conversion from microwave to optical signal with phase-shift keying (PSK) is achieved. The optical signal is subsequently demodulated through delayed homodyne. The system excels in the wide tunability of the subcarrier frequency. The frequency can be tuned continuously several times beyond the original relaxation resonance frequency of the laser [3,4]. So the system can easily adapt to changes of the uplink operation frequency. Furthermore, the system requires no high-speed electronics for demodulation.

Figure 1 shows the experimental setup. The semiconductor lasers used are 1.55 μm 2.5-Gbps-grade single-mode distributed feedback lasers (Mitsubishi ML920T43S-01). A master laser at the central office optically injects, through an optical circulator, into a slave laser at the base station. The setup is built back to back for demonstration. The master laser is temperature controlled at 18.00°C and biased at 133.70 mA. The slave laser is temperature controlled at 27.00°C and biased at 40.00 mA, emitting about 8.1 mW. The optical circulator is used to prevent mutual injection. The master laser operates at a continuous-wave optical frequency of ν_i, which is detuned by $f_i = 3.5$ GHz above the free-running frequency of the slave laser. A power of $P_i = 1.9$ mW is in-

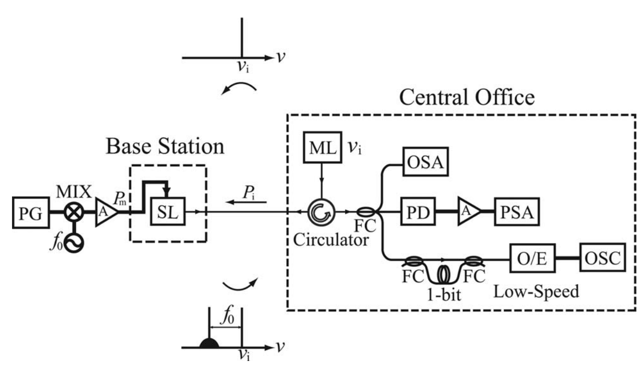

Fig. 1. Schematic of the experimental setup. ML, master laser; SL, slave laser; PG, pattern generator; MIX, mixer; FC, fiber coupler; OSA, optical spectrum analyzer; PSA, power spectrum analyzer; PD, photodetector; A, amplifier; OSC, oscilloscope; O/E, optical-to-electrical converter.

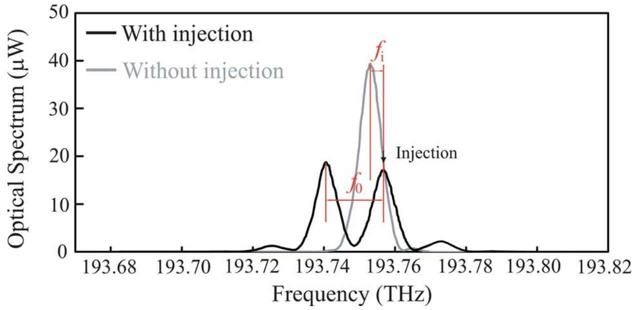

Fig. 2. (Color online) Optical spectrum of the upstream signal with no current modulation applied. The gray curve is obtained with no optical injection. The black curve is obtained with optical injection. The arrow indicates the regeneration from the optical injection. P1 oscillation at $f_0 = 16$ GHz is observed. (Resolution bandwidth, 7.5 GHz.)

jected into the slave laser, driving it into P1 oscillation of frequency $f_0 = 16$ GHz and changing the emission power by about 5%. The optical spectrum thus comprises the regeneration at ν_i and a generated component at $\nu_i - f_0$.

An uplink signal is obtained by electrically mixing a pseudorandom binary sequence at 180 Mbps generated by a pattern generator (Agilent N4906B) with a microwave source at f_0 generated by a microwave source (Agilent 83620B). After a microwave amplifier (Agilent 83017A), the signal with power P_m modulates the bias current of the slave laser directly. Attributed to the optical injection, the high-frequency response of the slave laser is greatly enhanced. The generated P1 signal at $\nu_i - f_0$ is modulated with the PSK signal accordingly. The uplink microwave PSK signal is thus converted to an optical PSK signal. Although some residual amplitude modulation is contained in the signal, it is more than 15 dB weaker than the phase modulation and so can be ignored.

Then the upstream light from the slave laser is split into three branches. In each branch the power is controlled at around 0.5 mW. One branch is monitored by an optical spectrum analyzer (HP 86142A). Another one is monitored by a 43 GHz photodetector (Newport AD-10ir), amplified by a microwave amplifier (Agilent 83006A), and sent to a power spectrum analyzer (Agilent N9010A). The third branch is sent to a delay-line interferometer of one-bit delay for differential PSK demodulation. Because the demodulated signal is contained in the baseband, a low-speed optical-to-electrical converter is used. The converter consists of a photodector (New Focus 1014) and a 1 GHz microwave amplifier (Mini-Circuits ZFL-1000LN). The signal is then monitored by an oscilloscope. Thus, an optical delayed homodyne detection is realized, and the signal is demodulated in the optical domain without using any high-speed electronics.

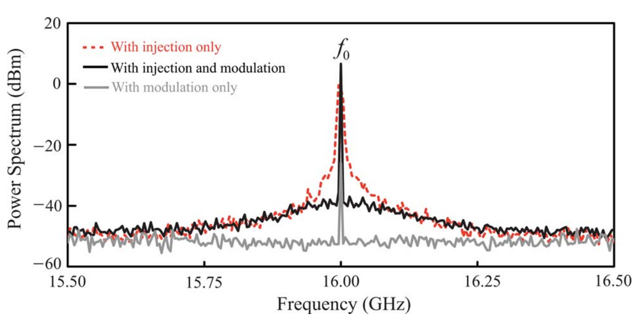

Fig. 3. (Color online) Power spectrum of the upstream signal. The dashed curve is obtained with optical injection only. The black curve is obtained under both optical injection and sinusoidal current modulation at f_0. The gray curve is obtained with current modulation but not optical injection. (Resolution bandwidth, 300 kHz.)

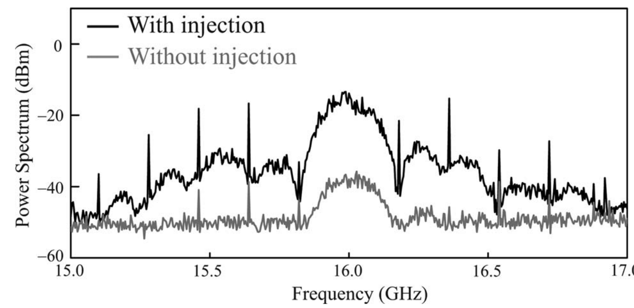

Fig. 4. Power spectrum of the upstream signal modulated with 180 Mbps PSK uplink signal. The black curve is obtained with optical injection. The gray curve is obtained without optical injection.

The experimental results are presented as follows. To begin with, the current modulation to the slave laser is turned off. Figure 2 shows the optical spectrum. The gray curve is obtained when no optical injection is applied. There is only one peak at the free-running frequency of the slave laser. The black curve is obtained when the optical injection with detuning frequency f_i is applied. The spectrum consists of a peak regenerated from the injection and a peak generated by the P1 nonlinear dynamics, which are separated by $f_0 = 16$ GHz. Note that the resolution is limited by the instrument to 7.5 GHz. It should be emphasized that the P1 frequency f_0 can be widely tuned between 10 and 100 GHz when the injection parameters (P_i, f_i) are varied [3,4].

The beating of the two peaks results in the power spectrum shown as the dashed curve in Fig. 3. Owing to the spontaneous emission noise and the intrinsic fluctuation of the system, the beat signal has a microwave linewidth on the order of 10 MHz. However, after a current modulation at f_0 with microwave power $P_m = 8.73$ dBm is switched on, the P1 oscillation can be stably locked at f_0. The black curve in Fig. 3 shows significant microwave linewidth reduction. Such a technique is referred to as double-locking, where a

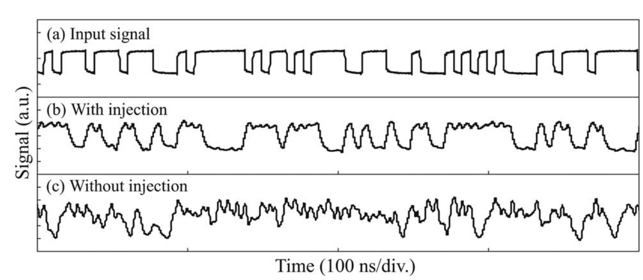

Fig. 5. Differential demodulation of data. (a) Input signal. (b) Recovered signal when optical injection is applied. (c) Recovered signal when optical injection is off.

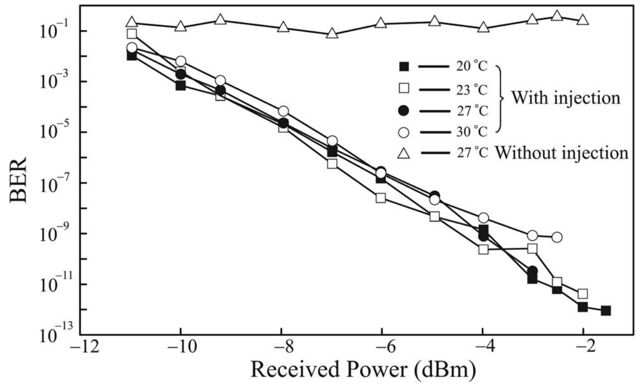

Fig. 6. BER as a function of the received optical power under different temperatures as indicated. Optical injection remains on, except for the open triangles.

narrow-linewidth photonic microwave is obtained [1]. The laser does not respond to current modulation well when optical injection is removed, producing the gray curve in Fig. 3, where the signal is more than 30 dB weaker. Therefore, optical injection is necessary for enhancing the laser response at the subcarrier frequency f_0.

Furthermore, when data are switched on as shown in Fig. 1, it mixes with the microwave source at f_0 and modulates the slave laser as an uplink PSK signal. Figure 4 shows the P1 oscillation modulated by the microwave PSK signal measured at the power spectrum analyzer. The microwave power P_m modulated onto the slave laser is 9.34 dBm. With optical injection, the black curve clearly shows the envelope of data. However, when the optical injection is removed, the signal diminishes as indicated by the gray curve. Although some signal is shown around 16 GHz, it is much weaker than the signal with optical injection.

Optical data recovery from the modulated P1 oscillation through the delay-line interferometer is observed at the oscilloscope. The aligned time traces of such differential demodulation are shown in Fig. 5. When optical injection is applied, the output signal in Fig. 5(b) gives "1" if and only if the adjacent bits in the input signal of Fig. 5(a) are different. The signal quality is quantified by the bit-error rate (BER) of around 10^{-11}. Figure 5(c) shows that when the optical injection is removed, the signal cannot be demodulated correctly. Optical injection is essential for the system.

It is well known that semiconductor lasers are very sensitive to temperature. Variation of the ambient temperature can lead to degradation of the system. To examine the temperature tolerance of the system, the temperature of the slave laser in the base station is varied from 20.00°C to 30.00°C; the range is currently limited by our temperature control circuit. Although the P1 oscillation frequency f_0 is temperature dependent, it can be kept constant by controlling the injection from the central office. The P1 oscillation frequency can be kept at 16 GHz by varying P_i between 1.8 mW and 4.0 mW and f_i between 1.1 GHz and 3.5 GHz. Figure 6 shows the BER of the system at different temperatures. Under a constant temperature, the BER clearly decreases as the received power increases. For a BER of 10^{-9} the system has a tolerance range of at least 10°C.

We have demonstrated all-optical demodulation in an RoF uplink transmission using a semiconductor laser under both optical injection and current modulation. Under proper injection, the laser exhibits P1 oscillation, which is further locked by the uplink microwave signal. An optical delay-line interferometer is used to demodulate the signal differentially. No high-speed electronics are required. The system excels in tolerance for temperature variation through compensation from the injection. Using a modest 2.5-Gbps-grade laser, RoF uplink at 16 GHz is successfully demonstrated.

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