

Radio-over-fiber AM-to-FM upconversion using an optically injected semiconductor laser

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A radio-over-fiber system uses light to carry a microwave subcarrier on optical fibers. The microwave is usually frequency modulated for wireless broadcasting. A conventional optical communication system usually operates at the baseband with amplitude modulation. The interface of the two systems thus needs an upconversion from the baseband to the microwave band with AM-to-FM transformation. An all-optical solution employing an optically injected semiconductor laser is investigated. The laser is operated in a dynamic state, where its intensity oscillates at a microwave frequency that varies with the injection strength. When the injection carries AM data, the microwave is frequency modulated accordingly. We demonstrate optical conversion from an OC-12 622-Mbps AM baseband signal to the corresponding FM microwave signal. The microwave is centered at 15.90 GHz. A bit-error rate of less than 10^{-9} is measured. © 2006 Optical Society of America

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Radio-over-fiber (RoF) has attracted much attention as a convenient way of distributing microwave signals.¹ In a RoF system, a central office is connected to remote base stations by optical fibers, where carrying microwave subcarriers are transmitted. At the base stations, photodetectors recover the microwave signals, which are then radiated to the wireless customer units.² RoF has the advantages of centralizing the high-speed electronics in the central office and allowing effective long-distance microwave transmission. Semiconductor laser sources for RoF include directly modulated lasers,³ multisection lasers,² and optically injected lasers.⁴

Data are usually carried by microwave through frequency modulation (FM) or phase modulation.⁵ Amplitude modulation (AM) is not preferred because of the wireless channel fading. In contrast, a conventional optical communication system usually employs baseband AM because of its simplicity. When a conventional system is connected to an RoF system, an interface is required for baseband-to-microwave upconversion with simultaneous AM-to-FM transformation. Although the interface can be realized by electrically modulating an RoF light source by using the photodetected signal of the baseband AM, a simple all-optical method bypassing the electronics is preferred. In this Letter a method is demonstrated. It employs an optically injected semiconductor laser. AM-to-FM upconversion is achieved by controlling the nonlinear dynamics.

It is well known that a semiconductor laser under proper optical injection undergoes microwave oscillation in its intensity. The microwave oscillation frequency is dependent on the strength of the injection.⁶ As a result, when the laser is injected by an AM base-

band optical signal, it generates a corresponding FM microwave signal. The FM microwave thus obtained has a wide tunability and a large modulation bandwidth.⁷ Such AM-to-FM upconversion of data by simply injecting the AM optical signal into a semiconductor laser has not been reported to our knowledge. It is demonstrated as follows.

Figure 1 shows the experimental setup. The semiconductor lasers used are $1.3\text{ }\mu\text{m}$ single-mode distributed-feedback lasers (Bookham Technology LC131). The slave laser is temperature stabilized and is biased at 2.22 times its threshold, emitting about 4.5 mW of power. About 5 mW of light from the master laser is directed to the facet of the slave laser using a free-space circulator arrangement that consists of a polarizing beam splitter, a Faraday rotator, and a half-wave plate. Owing to imperfect alignment and coupling, only a small portion of this light is successfully injected into the slave laser. Comparison of the resultant dynamics to numerical results⁶ reveals an actual injection strength of about 0.05. The injection strength is defined as a normalized quantity, which is roughly equal to the ratio of the electric field of the injection to that of the free-running slave laser. Optimizing the injection coupling and polarization can potentially reduce the injection power to the order of $10\text{ }\mu\text{W}$. Although the frequency of the slave laser in the absence of injection is detuned by 3.7 GHz below that of the master laser, the injection is strong enough to lock it to the frequency of the master laser. Under the proper injection strength, the slave laser enters the period-one (P1) state. The output intensity oscillates at a microwave frequency that depends on the injection strength and the frequency detuning. An optical wave carrying a microwave signal is gen-

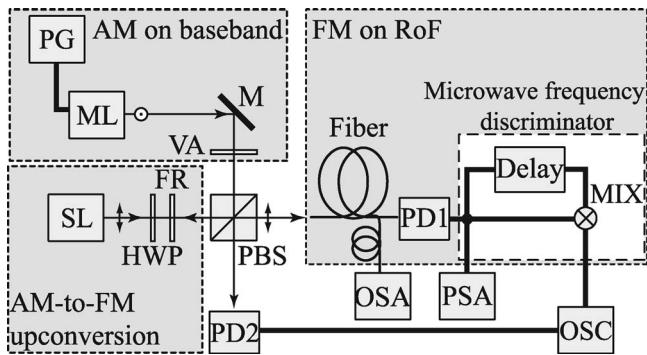


Fig. 1. Schematic of the experimental setup. ML, master laser; SL, slave laser; M, mirror; VA, variable attenuator; PBS, polarizing beam splitter; FR, Faraday rotator; HWP, half-wave plate; PD, photodiode; MIX, mixer; PG, pattern generator; PSA, power spectrum analyzer; OSC, digital sampling oscilloscope; OSA, optical spectrum analyzer.

erated. At a fixed master–slave frequency detuning, the microwave frequency increases with the injection strength approximately linearly over a large range. At a fixed injection strength, the microwave frequency also varies approximately linearly with the injection detuning. The P1 frequency has a large tuning range from 10 GHz (the relaxation oscillation frequency of the slave) to at least 100 GHz. The P1 characteristics of this laser were studied previously.^{6–8}

The master laser can be current modulated by a pattern generator with a $2^7 - 1$ pseudorandom binary sequence at 622 Mbps (megabits per second, OC-12). It then emits light that carries a baseband AM signal with a 12% modulation depth, representing signals of a conventional optical communication system. It is injected into the slave laser and controls the microwave frequency of the P1 state. Because the microwave frequency varies with the injection strength linearly, the AM of the injection is transformed into FM of the microwave with little distortion. The slave laser thus acts as an AM-to-FM upconverter. As in an RoF system, the laser output is an optical wave that carries an FM microwave signal and is transmitted through an optical fiber with about 1.28 mW of power. The modulation depth of the FM increases with that of the AM, but the laser has to remain in the P1 state. This constraint translates into a maximum AM modulation depth of about 90% for our system.

The fiber shown in Fig. 1 represents the optical transmission channel. Although the fiber length is only a few meters in our proof-of-concept experiment, it can be extended to hundreds of kilometers in a real system. The optical spectrum of the signal is monitored by an optical spectrum analyzer (Advantest Q8347), and the power spectrum is monitored by a power spectrum analyzer (HP E4407B) after photo-detection by using a 35 GHz photodiode, PD1. The output of PD1 is a microwave signal with FM around the central frequency. It is to be radiated by a base station to customer units in a real system. However, in our demonstration, it is sent directly to a microwave frequency discriminator for FM demodulation. The function of the discriminator is to electrically mix the microwave signal with its delayed replica.

The delay is set at a quarter-period of the central microwave frequency so that the output of the mixer is proportional to the instantaneous frequency deviation from the central frequency.⁷ The mixer gives the demodulated signal, and it is monitored by a digital sampling oscilloscope (Tektronix TDS8000). The result is compared with the input AM baseband signal that is detected by PD2.

The experiment is first conducted with the AM of the optical injection light switched off so that a steady-state P1 state is obtained. Because of the bandwidth limitation of our available detection electronics, we will focus on the P1 state of a relatively low frequency of 15.90 GHz. We emphasize that this frequency can be as high as 100 GHz with our existing lasers. Thus it is not a limiting factor for a practical system. The optical spectrum of the slave laser is shown in Fig. 2 with a 900 MHz resolution bandwidth. The injection locks the slave laser and directly gives the frequency component indicated by the arrow. It also drives the laser into the P1 state that produces sidebands separated by 15.90 GHz. Notice that the sidebands are highly asymmetric. While the amplitude of the lower sideband is about the same as the injected component, the upper sideband is 13 dB weaker. This nearly single-sideband behavior is desirable in RoF systems because it circumvents the microwave power penalty induced by fiber chromatic dispersion.

The beating of the optical frequency components results in an oscillation of optical power. The power spectrum is shown as the dark curve of Fig. 3. A microwave linewidth of the order of 10 MHz is observed, which is caused by the spontaneous emission and the charge-carrier fluctuations in the slave laser. Although it does not pose major problems to our experiment, the frequency can be stabilized through microwave locking techniques if necessary.^{4,9} With the AM switched on, the frequency of the P1 state is modulated. The gray curve of Fig. 3 shows the correspondingly broadened spectrum. The frequency is switched between 15.23 GHz and 16.40 GHz when the injection strength is low and high, respectively. The frequency separation increases if the modulation depth of the AM injection increases.

The quality of the AM-to-FM upconversion is evaluated from the eye diagrams in Fig. 4 recorded from the oscilloscope. The input baseband AM of the

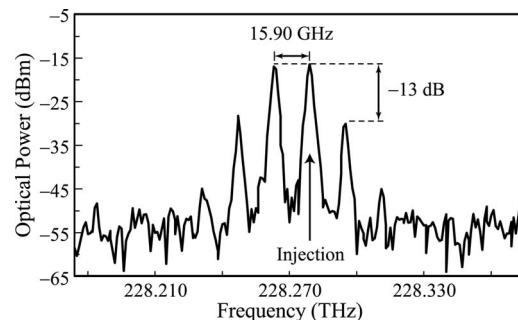


Fig. 2. Optical spectrum of the slave laser locked by the master into P1 oscillation. The sidebands separated by 15.90 GHz from the injection are due to the dynamical oscillation. (Resolution bandwidth, 900 MHz.)

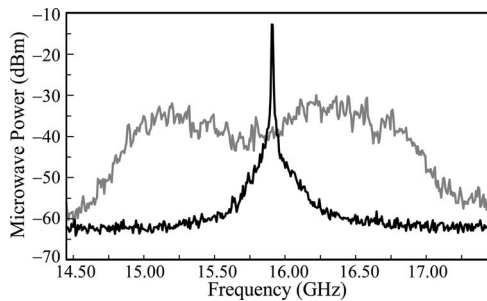


Fig. 3. Power spectrum of the slave laser. The dark curve is obtained from the steady-state period-one oscillation under constant injection. The gray curve is obtained from the frequency-modulated period-one oscillation under AM injection. (Resolution bandwidth, 3 MHz.)

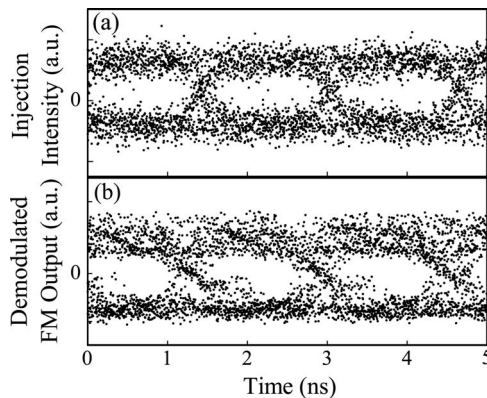


Fig. 4. Eye diagrams of (a) the variation of the optical injection intensity from the master laser under AM, and (b) the demodulated FM signal of the microwave generated by the slave laser.

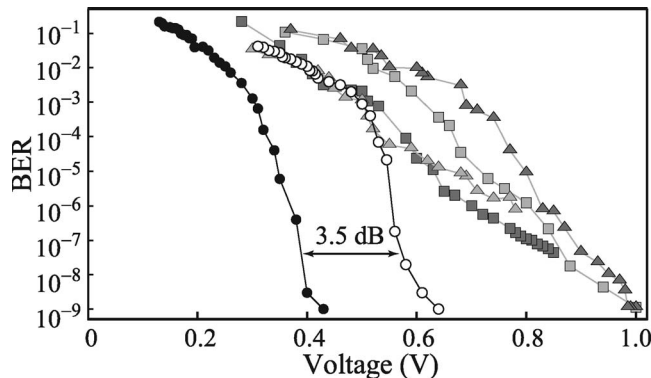


Fig. 5. BER as a function of the signal peak-to-peak voltage. Closed circles, input AM signal after PD2. Open circles, demodulated FM signal for the original P1 state. Gray points, demodulated FM signal for other P1 states. The relative injection power (normalized to the original P1 state), injection detuning (GHz), and P1 frequency (GHz) are, respectively, open circles (1, 3.7, 15.9), dark triangles (1, 7.1, 17.2), light triangles (1, -0.8, 14.6), dark squares (1.7, 3.7, 17.4), and light squares (0.5, 3.7, 12.8).

injection intensity as directly detected by PD2 is shown in Fig. 4(a). The output microwave FM is demodulated by the discriminator and is shown in Fig. 4(b), which shows only slight signal degradation. The degradation is examined by measuring the bit-error

rate (BER) as a function of the signal voltage in Fig. 5. First ignoring the gray curves, the BER of the AM input is compared with that of the demodulated FM output, which are respectively shown as closed and open circles. Comparison of the BER shows a 1.5 times increase or a 3.5 dB penalty on the signal voltage. An output BER of less than 10^{-9} can be obtained. The generated microwave also contains a small AM component, but the modulation depth is less than 5%. The data for other P1 frequencies under various injection conditions are shown as the gray points in Fig. 5, although the response of our discriminator is not optimized at these frequencies. We also examine a P1 state at 100 GHz when the injection power is doubled and the detuning is increased to 90 GHz. The optical spectrum shows spectral broadening of the P1 oscillation under a modulated injection. The method is applicable to high frequencies.

We have demonstrated all-optical conversion of an AM baseband signal into a FM microwave signal for RoF applications. Our demonstration is restricted by the bandwidths of the detection electronics, but the optical injection system itself is capable of high-frequency operation with a very large bandwidth. By varying the optical injection strength or the detuning frequency, the microwave frequency can be varied widely from 10 GHz to at least 100 GHz.⁷ As long as the laser is maintained in the period-one dynamic, the modulation depth of the output FM increases linearly with that of the input AM. A maximum frequency deviation of more than 10 GHz can be achieved.⁶ According to the broad frequency response of the system from dc to more than 1 GHz,⁷ the data can contain low-frequency components (or long strings of zeros), and the data rate can be increased. The system can also be applied for generating a frequency-hop spread spectrum when the injection strength is switched among multiple levels.

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References

- U. Gliese, *Opt. Quantum Electron.* **30**, 1005 (1998).
- D. Novak, G. H. Smith, A. J. Lowery, H. F. Liu, and R. B. Waterhouse, *Opt. Quantum Electron.* **30**, 1021 (1998).
- A. Kaszubowska, P. Anandarajah, and L. P. Barry, *IEEE Photon. Technol. Lett.* **16**, 605 (2004).
- T. B. Simpson and F. Doft, *IEEE Photon. Technol. Lett.* **11**, 1476 (1999).
- U. Gliese, T. N. Nielsen, S. Nørskov, and K. E. Stubkjær, *IEEE Trans. Microwave Theory Tech.* **46**, 458 (1998).
- S. K. Hwang, J. M. Liu, and J. K. White, *IEEE J. Sel. Top. Quantum Electron.* **10**, 974 (2004).
- S. C. Chan and J. M. Liu, *IEEE J. Quantum Electron.* accepted for publication.
- S. K. Hwang and J. M. Liu, *Opt. Commun.* **183**, 195 (2000).
- S. C. Chan and J. M. Liu, *IEEE J. Sel. Top. Quantum Electron.* **10**, 1025 (2004).