Generation and Modulation of Tunable mm-Wave Optical Signals Using Semiconductor Ring Laser

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***Abstract*—Optical injection locking and cavity enhanced four-wave mixing in semiconductor ring lasers have been used to generate data modulated millimeter (mm)-wave optical signals. The scheme is shown to have multigigahertz (multi-GHz) modulation bandwidth. The 4-Gb/s data is transferred directly from an intensity modulated optical signal onto an mm-wave optical signal with the mm-wave frequency tunable in steps of 62.5 GHz and with flexible radio-frequency modulation formats over the optical carrier. Bit-error-rate and eye-diagram measurements confirm excellent signal quality.**

***Index Terms*—Four-wave mixing (FWM), millimeter (mm)-wave modulation, optical injection locking (OIL), radio-frequency (RF)-over-fiber, semiconductor ring laser (SRL).**

I. Introduction

RADIO-OVER-FIBER (RoF) communication systems with high data rate have the potential to fulfil the future requirements of wireless broadband communications as they can utilize the low loss and ultrawide bandwidth provided by optical fiber. Radio-frequency (RF) signal generation and modulation are crucial for RoF systems. Several different schemes are used to generate and modulate RF signals by utilizing mode-locking (ML) in semiconductor lasers [1], a combination of laser direct and external modulation [2] to impart electronic data onto the RF optical carrier.

The semiconductor ring laser (SRL) is currently receiving much research interest as a nonlinear optical device [3], [4]. Due to its strong bistability stemming from the strong nonlinear mode interactions [4], SRLs can be used for all-optical logic operations [5], all-optical pulse reshaping and retiming (2R/3R) [6], and optical memory [7].

Recently, it was reported that external optical injection on nonlasing cavity mode of SRL generates strong cavity enhanced four-wave mixing (FWM) [8] which results in the generation of optical waves modulated by high purity RF frequencies as a result of the ML by way of such FWM. Although FWM were observed in FP lasers before [9], the efficiency and optical bandwidth demonstrated in SRL are several orders of magnitude higher. This makes the SRL attractive for the generation of millimeter (mm)-wave modulated optical signals that may be used in RoF systems.

In this letter, we report, for the first time, the generation and wideband modulation of mm-wave optical signals using a combination of optical injection locking (OIL) and FWM in the SRL. OIL has been shown to enhance the bandwidth of semiconductor laser in both direct and optical modulation [10]. We demonstrate that ordinary intensity modulated (IM) optical data up to 4 Gb/s can be converted onto the mm-wave optical carrier, with the mm-wave frequency widely tunable up to hundreds of gigahertz (GHz) and with excellent data quality. The scheme can be used for the downlink [11] in optical transmission for wireless communication systems.

II. Device and Experimental Setup

The device used is a monolithically integrated four-port SRL fabricated on a 1550-nm multiple quantum-well AlGaInAs–InP wafer at Glasgow University. The racetrack-shaped device has two semicircular sections with 200-μm radius and two 75-μm straight sections. The cavity free spectrum range (FSR) is 0.5 nm or 62.5 GHz. Two access waveguides are coupled to the main cavity by forming directional couplers with the straight sections, providing a $\sim$30% coupling ratio. The access waveguides form a 10° angle with the cleaved bar facets to minimize back-reflection. The device was tested with a continuous-wave threshold of 30 mA at 17.5 °C and above 37 mA the directional bistability occurs, where the operation of the laser is either in the clockwise (CW) or counterclockwise (CCW) direction, with a single-mode lasing spectrum of $>$30-dB sidemode suppression ratio (SMSR) at the operating current of 128 mA.

Fig. 1 illustrates the experimental setup. A tunable laser (TL1) is used to provide a holding beam (HB) to injection-lock the SRL at one of its cavity modes (m_0) in the CCW direction. A second tunable laser (TL2) is IM using a $LiNbO_3$ Mach–Zehnder modulator (MZM) by signals from a pulse pattern generator (PPG) or an Agilent E8364A vector network analyzer (VNA) and it is tuned to either m_1, m_2, or m_3 to create FWM. This modulated optical signal together with the HB is injected to the SRL through port P1 with their polarization adjusted to maintain transverse-electric (TE) input. In practice, as demonstrated in [8], the HB input is not essential for the FWM experiment once the SRL lasing direction is set, as the SRL will continue to operate in that direction. The output signal

Manuscript received November 04, 2008; revised February 11, 2009. First published March 24, 2009; current version published May 15, 2009. This work was supported by the EU FP6 under project "IOLOS." The work of M. I. Memon was supported by the COMSATS Institute of Information Technology Islamabad, Pakistan.

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Digital Object Identifier 10.1109/LPT.2009.2017383

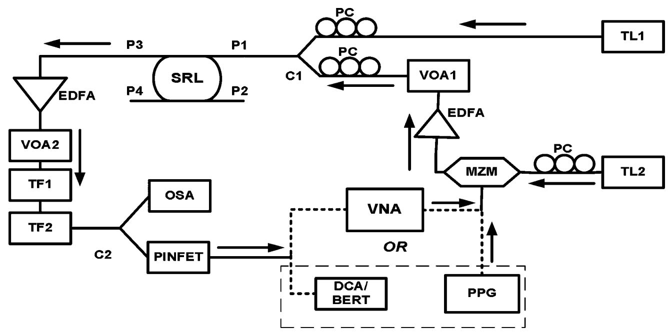

Fig. 1. Experimental setup.

power from port P3 is adjusted by an erbium-doped fiber amplifier (EDFA) and variable optical attenuators (VOAs) before being filtered using tunable bandpass filters TF1 and TF2. The filtered output is split using a 3-dB coupler C2, and is passed to the optical spectrum analyzer (OSA) as well as detected by a 10-Gb/s p-intrinsic-n field-effect transistor (PINFET). The PINFET output is analyzed by a bit-error-rate (BER) tester, a digital communications analyzer (DCA), or the VNA.

III. Experimental Results and Discussion

The SRL was biased at 128 mA and the two access waveguides between the SRL and P1 or P3 were biased at 35 mA (transparency current ~5 mA), which provides some gain to partially offset the coupling loss between the fiber and the SRL. Its temperature was maintained to 17.5 °C $\pm$ 0.1 °C using a thermoelectric controller.

The SRL is strongly injection-locked at a mode by the HB from TL1. As a result, the selected mode (denoted by m_0) becomes predominant with a high SMSR of >40 dB as shown in the first spectrum of Fig. 2. The modulated second optical beam from TL2 (with 100% data modulation depth) is injected at a sidemode (e.g., m_2). In-fiber optical power from TL1 and TL2 are adjusted to 10 and 0 dBm, respectively, with a fiber-chip coupling loss of ~10 dB. Due to cavity enhanced FWM that couple the optical fields between the modes that satisfy phase matching and photon energy conservation conditions, several equally spaced modes are created mirrored around mode m_0, and are locked in phase. Fig. 2 gives the spectra with modulated injection on m_1, m_2, and m_3, respectively. Under this condition, standard ML theory indicates that beating between the modes results in a periodical modulation of the optical signal with a frequency equal to the frequency spacing between the modes, as already experimentally characterized in [8] showing excellent RF tone purity. In the cases of Fig. 2, the generated RF frequency is $1\times$, $2\times$, or $3\times$ of the SRL FSR of 62.5 GHz. Furthermore, because one of the injection signals is modulated by a data pattern or the VNA output, this RF optical carrier is also modulated by the same data pattern or the VNA output.

A particular problem in RoF transmission is fading due to fiber dispersion, which can be overcome using modulation formats such as single sideband (SSB) modulation [1]. From the ML spectra, a pair of modes (such as m_{-2} and m_{-4} in Fig. 2) is isolated by adjusting TF1 and TF2 in such a way that both

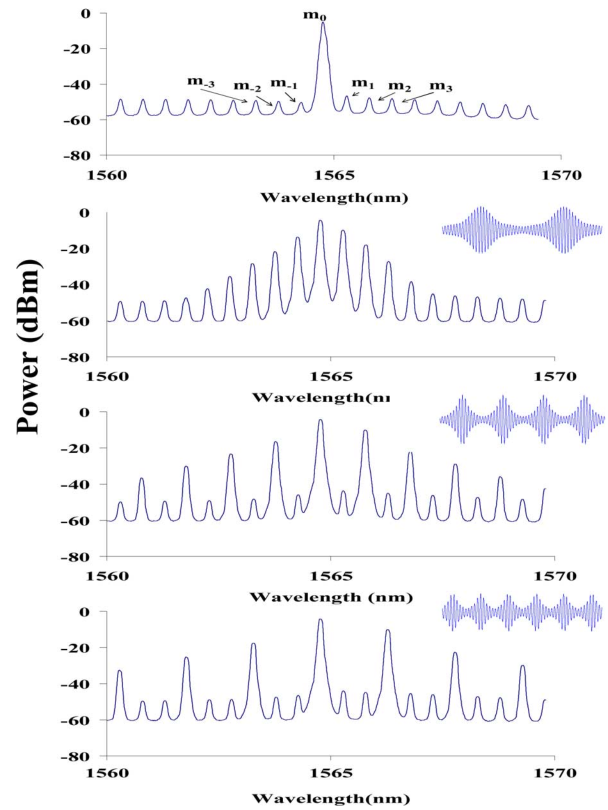

Fig. 2. Optical spectra of OIL SRL with no second external injection (top), and with second external signal injected on the m_1, m_2, and m_3, respectively. Insets are the time-domain illustration of optical waveform in each case, composed from the spectra.

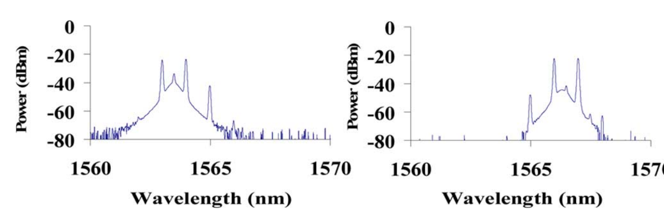

Fig. 3. Optical spectrum of 125-GHz signals S_{-1} (left) and S_1 (right).

modes have the same power level as shown in Fig. 3(left), creating an optical carrier that is single sideband modulated by the RF or mm-wave, with the RF or mm-wave in turn amplitude modulated by the data. We did not use 62.5-GHz frequency because narrowband optical filters are not available to us.

In RoF systems, usually data is extracted from high-frequency carrier through the down-conversion process in a mixer. But in our system, the filtered signals S_1 and S_{-1} are directly detected using the PINFET for modulation bandwidth, eye diagram, and BER measurements. Due to the slow response of PINFET compared to the mm-wave carrier frequency, the electrical output of the PINFET contains only the base-band data as the carrier is cut off. The respective small signal modulation frequency response of the detected signals S_1 and S_{-1} is measured using the VNA with 0-dBm output power. The test system including the modulator and PINFET has ~7.5-GHz 3-dB bandwidth, and its back–back response is first measured. The frequency response of S_1 and S_{-1} are normalized to the

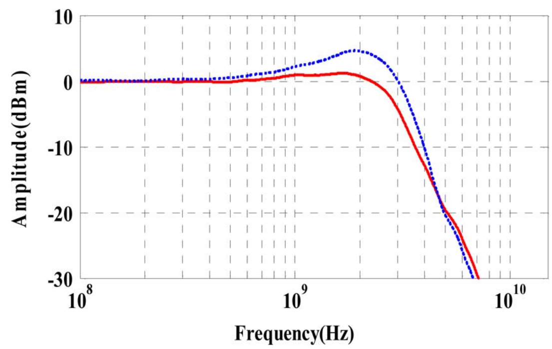

Fig. 4. Modulation frequency response of S_1 (solid line) and S_{-1} (dotted line).

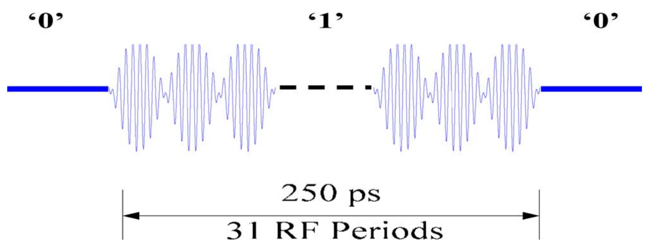

Fig. 5. Time-domain representation of the data modulated 125-GHz RF optical signal.

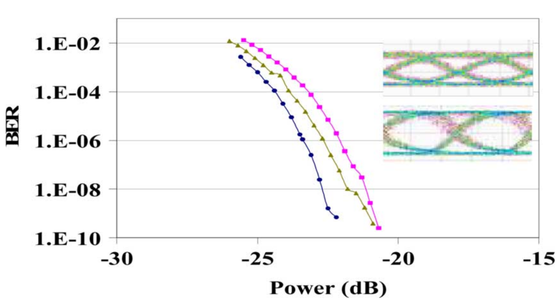

Fig. 6. BER curves for back–back, S_1 and S_{-1} (left to right), respectively. Insets: Eye diagrams for S_{-1} (upper) and S_1 (lower).

back–back response, and shown in Fig. 4. The 3-dB bandwidth of both signals is >3 GHz.

With 4-Gb/s pseudorandom binary sequence data modulating the input beam, the time domain representation of the generated mm-wave optical signals S_1 and S_{-1} is shown in Fig. 5. Only when data is "1" the ML takes place. When data is "0", there is no injection power at m_2, and the SRL reverts back to single-mode lasing at m_0. After filtering, m_0 is suppressed; therefore, there is little power during data "0", while in each "1" bit, there are 31 periods of mm-wave signals forming an SSB modulation waveform.

The BER measurements for back–back, S_1 and S_{-1} at 4 Gb/s are given in Fig. 6. Compared to back–back, both signals have <2-dB receiver power penalties at BER of 10^{-9}. The main difference between eye-diagrams of S_1 and S_{-1} is the power level. S_1 is a combination of m_2 and m_4. It has more power because m_2 is directly excited by input modulated signal and m_4 is generated by FWM between m_2 and m_0. S_{-1} is a combination of m_{-2} and m_{-4}. m_{-2} is generated by FWM so it is weaker than m_2. m_{-4} is in turn generated by further FWM between m_{-2} and m_0, therefore, is weaker than m_4.

IV. Conclusion

We demonstrated a method for the efficient generation and wideband modulation of mm-wave optical signals using a combination of OIL and FWM in the SRL. IM optical data up to 4 Gb/s has been directly converted onto an RoF carrier, with excellent data quality. The RF frequency is widely tunable in steps of 62.5 GHz (or FSR of the SRL) with potentially very narrow RF linewidth. Various RF modulation formats such as amplitude modulation, SSB, etc., can be generated by simple optical filtering either at source or at receiver. This scheme readily lends itself for monolithic integration, as already demonstrated in [13].

Acknowledgment

The authors would like to thank Dr. G. Guilani, University of Pavia, for helpful discussions.

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