IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 19, NO. 3, FEBRUARY 1, 2007

Harmonic Millimeter-Wave Generation and Frequency Up-Conversion Using a Passively Mode-Locked Multisection DFB Laser Under External Optical Injection

Kwang-Hyun Lee, Woo-Young Choi, Young Ahn Leem, and Kyung Hyun Park

***Abstract*—We demonstrate that a passively mode-locked multisection distributed-feedback (PML-MS DFB) laser can perform both harmonic millimeter-wave generation and harmonic frequency up-conversion under the external optical injection. Optical multiple modes generated by a PML-MS DFB laser produce harmonic millimeter-waves by mode-beating in a photodiode (PD), and the phase quality and stability are enhanced by the injection of external optical signal modulated at $f_{\rm LO}$. In addition, if the external optical signal is modulated simultaneously by $f_{\rm LO}$ and $f_{\rm IF}$, the PML-MS DFB laser performs all-optical frequency up-conversion producing sidebands at $f_{\rm LO} \pm f_{\rm IF}$ when detected by a PD. Using this method, we demonstrate generation of stable harmonic millimeter-waves at 30.42 and 60.84 GHz with $f_{\rm LO}$ of 15.21 GHz, and up-conversion of 10-Mb/s quadrature-phase-shift keying data at 150 MHz $f_{\rm IF}$ into the 60-GHz band. These functions of a PML-MS DFB laser can be useful for radio-over-fiber applications in which a compact optical source is needed for processing high-frequency radio signals in optical domain.**

***Index Terms*—Millimeter-wave generation, mode-locked lasers, up-converters.**

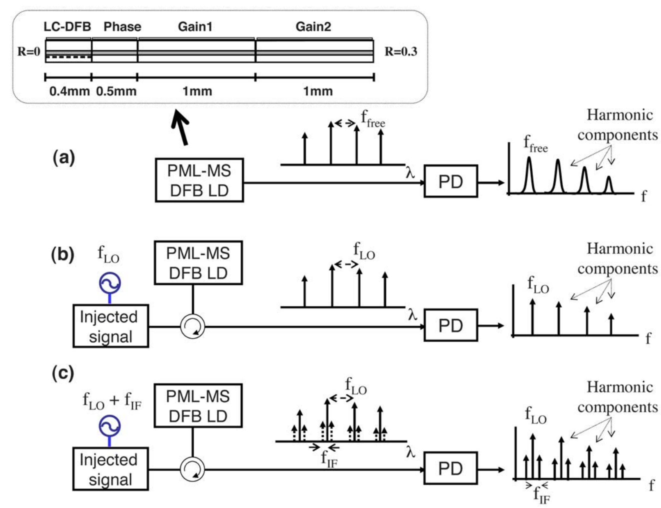

Fig. 1. Schematic explanations for (a) free-running, (b) injection locking with external optical signal modulated at $f_{\rm LO}$, (c) all-optical up-conversion of $f_{\rm IF}$ into $f_{\rm LO} \pm f_{\rm IF}$.

I. Introduction

MODE-LOCKED lasers have been actively investigated for the generation of millimeter waves [1]–[5]. They can generate stable harmonic millimeter-waves using the harmonic optical injection-locking technique, where external optical pulses modulated with the subharmonic frequency is injected into a passively mode-locked laser [1]–[3]. In particular, monolithic semiconductor mode-locked lasers are of great interest because of their compactness and stability [1]–[3].

Using mode-locked lasers with millimeter-wave generation capacity, the function of data up-conversion from the intermediate frequency $(f_{\rm IF})$ to the millimeter-wave band can be performed in the optical domain. Such a function is needed for realizing radio-over-fiber (RoF) systems for millimeter-wave band applications [6].

In this letter, we demonstrate that a single passively mode-locked multisection distributed-feedback (PML-MS DFB) laser under the external injection of RF modulated optical signal can produce harmonic millimeter-waves and, simultaneously, perform optical up-conversion. Millimeter-waves at 30.42 and 60.84 GHz corresponding to the second and fourth harmonics of the PML-MS DFB laser fundamental frequency are generated and their phase characteristics are enhanced by injection of the external optical signal modulated by $f_{\rm LO}$, close but not equal to the free-running frequency $(f_{\rm free})$ of the PML-MS DFB laser without injection. In addition, in order to up-convert $f_{\rm IF}$ into the desired millimeter-wave band, the external optical signal is simultaneously modulated by $f_{\rm IF}$ and $f_{\rm LO}$, resulting in optical sidebands separated from the optical modes by $f_{\rm IF}$. When these signals are detected by a photodiode (PD), desired up-converted IF signals are produced. As a demonstration of this optical up-conversion, 10-Mb/s quadrature-phase-shift keying (QPSK) data at 150 MHz are up-converted into 60-GHz band and the quality of the resulting up-converted data is characterized.

Manuscript received August 7, 2006; revised October 30, 2006.

K.-H. Lee and W.-Y. Choi are with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: wchoi@yonsei.ac.kr).

Y. A. Leem and K. H. Park are with the Electronics and Telecommunications Research Institute, Daejeon 302-350, Korea.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2006.889991

II. Operating Principle

Fig. 1 shows the operating principle of our scheme. The structure of the PML-MS DFB laser is also shown in the figure. It is composed of DFB, phase tuning, and two gain sections. Details

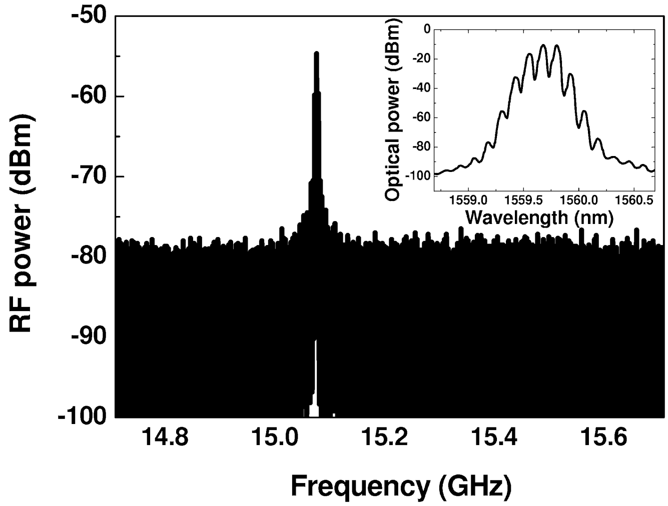

Fig. 2. Measured RF and optical spectrum for free-running PML-MS DFB laser with $I_{\mathrm{DFB}} = 30$ mA, $I_{\mathrm{Phase}} = 10$ mA, $I_{\mathrm{Amplifier1}} = 100$ mA, $I_{\mathrm{Amplifier2}} = 46$ mA.

of passive mode-locking characteristics of this device without a saturable absorber can be found in [7].

When the device is passively mode-locked, it has many optical modes separated by f_{free} determined by the cavity length. These optical modes can generate millimeter-waves corresponding harmonics of f_{free} by mode beating in a PD [Fig. 1(a)]. However, the broad linewidth of the generated electrical signals is not suitable for such application as phase modulated data signal transmission, often used in wireless communications. This problem can be solved by the injection of optical signal modulated at f_{LO} [Fig. 1(b)].

If the injected optical signal is modulated by both f_{LO} and f_{IF} as shown in Fig. 1(c), optical modes of PML-MS DFB laser are also modulated with f_{IF}, resulting in sidebands separated by f_{IF}. When these optical signals are detected by a PD, electrical sidebands are produced f_{IF} away from f_{LO}. Effectively, the PML-MS DFB laser performs frequency up-conversion of f_{IF} into $f_{\mathrm{LO}} \pm f_{\mathrm{IF}}$. Furthermore, many harmonic modes of the PML-MS DFB laser can be utilized for harmonic up-conversion in which f_{IF} can be up-converted into $nf_{\mathrm{LO}} \pm f_{\mathrm{IF}}$. This type of harmonic frequency up-conversion is very useful for such applications as RoF systems in which the function of up-conversion of the phase-sensitive digital data at f_{IF} into the desired millimeter-wave band is needed. [6].

III. Experimental Results

Fig. 2 shows the measured RF and optical spectrum of a PML-MS DFB laser without any external optical injection. The device was designed to have f_{free} at around 15 GHz. By changing the dc bias currents of DFB and gain sections, f_{free} can be tuned more than 1 GHz [7]. With many optical modes as shown in the optical spectrum, the device can produce many harmonic frequency components in RF domain by mode beating.

Fig. 3 shows the measured RF spectra of the locked signals detected by a PD. The power and the wavelength of the injected optical signal into the PML-MS DFB laser were about 6 dBm, 1570 nm, respectively, and the injected optical signal was modulated by 25-dBm RF signal at f_{LO} (15.21 GHz). In order to

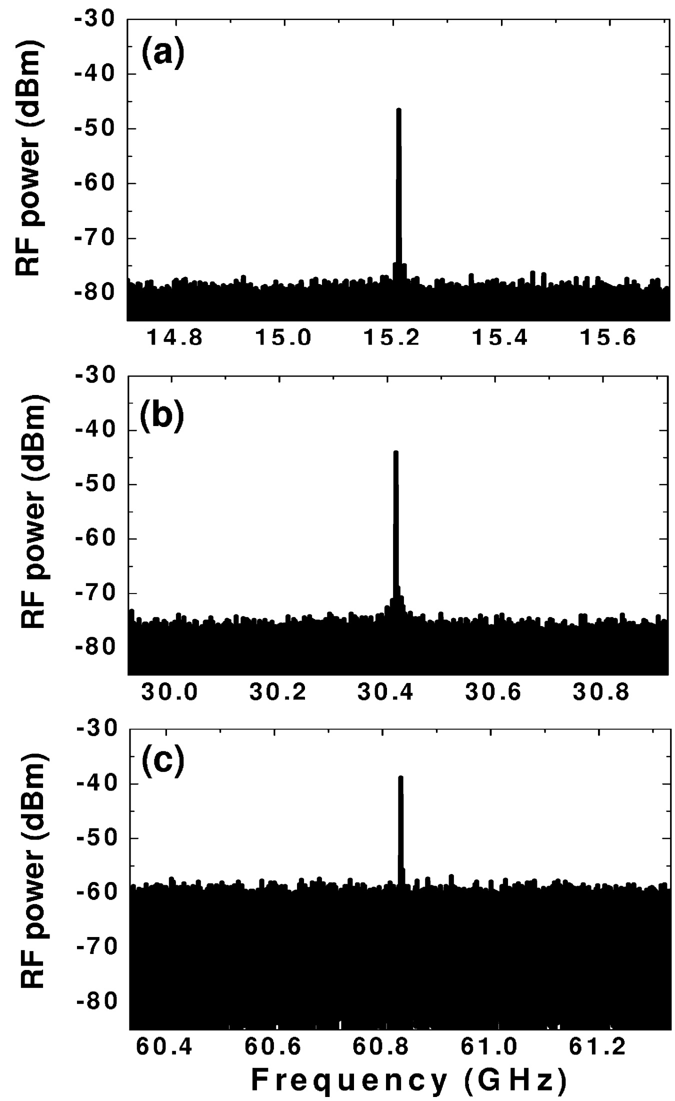

Fig. 3. Measured RF spectrum of PML-MS DFB laser under external injection locking for (a) fundamental-, (b) second-, and (c) fourth-harmonic component.

lock the PML-MS DFB laser, the external optical signal having f_{LO} slightly higher than $f_{\mathrm{free}}(\sim 15\ \mathrm{GHz})$ was needed. This is because external optical injection causes the shift of PML-MS DFB laser f_{free} due to carrier density variation [7].

The RF spectra of the fundamental component at 15.21 GHz, the second at 30.42 GHz, and the fourth at 60.84 GHz are shown in Fig. 3(a)–(c), respectively. The undesired noises near the peak appearing in Fig. 3(a) and (b) are believed to be due to the random modulation of PML-MS DFB laser originating from current sources [8] and the increased noise floors shown in Fig. 3(b) and (c) are due to external mixers (HP11970A for the second harmonic and HP11974 V for the fourth harmonic) used for measurement as well as two-stage low noise amplifiers having the total gain of about 35 dB used for the fourth harmonic.

To analyze the signal quality of the locked PML-MS DFB laser, we measured phase noises of the fundamental free-running and locked signals as well as the RF source used for modulating the injected optical signal. Fig. 4 shows the results. The measured phase noise value at 10-kHz frequency offset

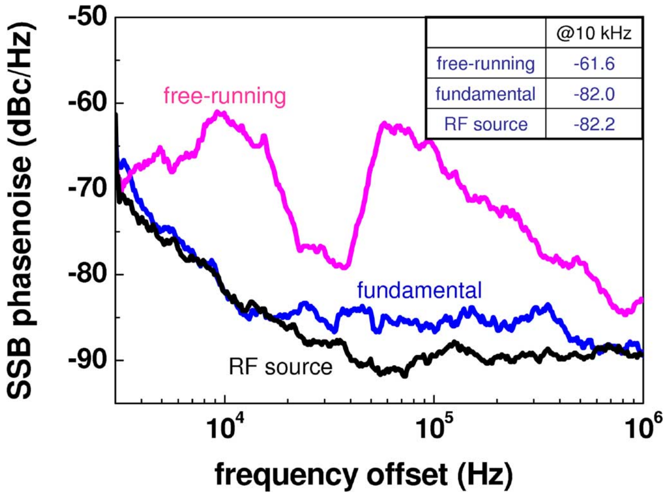

Fig. 4. Measured phase noises of the free-running and locked PML-MS DFB laser and the RF source.

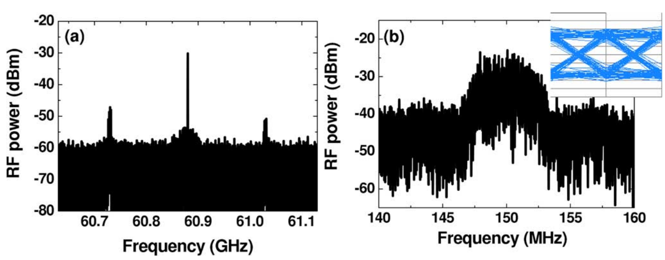

Fig. 5. Measured RF spectrum of (a) up-converted signals of 10-Mb/s QPSK data carried at 150 MHz, (b) output of self-heterodyne detection and eye diagram of the demodulated QPSK data.

for free-running, fundamental, and RF source is -61.6, -82.0, and -82.2 dBc/Hz, respectively. From this result, it can be confirmed that the phase quality of the generated signal is drastically improved by the optical injection. The measured phase noise values at 10-kHz frequency offset of the second- and fourth-harmonic components were -75.5 and -70.1 dBc/Hz, respectively, and each phase noise degradation of 5.5 and 12 dB as compared with the fundamental value well agrees with the theoretical value of 6 and 12 dB [9].

The external optical signal modulated with both f_{LO} and 10-Mb/s QPSK data at f_{IF} of 150 MHz was injected into PML-MS DFB laser to demonstrate frequency up-conversion. The RF spectrum of the fourth-harmonic up-converted data signals is shown in Fig. 5(a). We investigated the fourth-harmonic component since we intend to use this harmonic up-converter for 60-GHz RoF applications. The spectrum clearly shows up-converted double sideband data signals 150 MHz away from 60.84 GHz, the fourth harmonic of f_{LO}. The undesired noises near 60.84 GHz are believed to be due to random current modulation as in Fig. 3(a) and (b) (not shown in Fig. 3(c) because of the raised noise level). Since the generated fourth-harmonic signal power with 35-dB electrical amplification is about -30 dBm, the millimeter-wave generation power efficiency, defined as the power ratio between the RF signal used for modulating the injected optical signal (25 dBm) and the generated fourth-harmonic signal, is about -90 dB.

The up-converted data were evaluated by a 60-GHz self-heterodyne detector [10], and the resulting down-converted data were analyzed by the vector signal analyzer. Fig. 5(b) shows the down-converted RF spectrum and the eye diagram for the demodulated QPSK signal in the inset. The measured error vector magnitude was about 15.6%, in which the magnitude error was 11.0% and the phase error was 6.5°. The relatively large magnitude error was due to the low modulation efficiency induced by external optical injection, which can be improved by directly modulating PML-MS DFB laser with electrical signals.

IV. Conclusion

In this letter, we have experimentally demonstrated that the PML-MS DFB laser can perform both harmonic millimeter-wave generation and all-optical harmonic up-conversion. Using this, we successfully generated millimeter waves corresponding to the second- (30.42 GHz) and the fourth- (60.84 GHz) harmonic components with the injection of the modulated optical signal at $f_{\mathrm{LO}} = 15.21$ GHz. In addition, we demonstrated harmonic up-conversion of 10-Mb/s QPSK data carried at 150 MHz to the 60-GHz band. This capability of harmonic millimeter-wave generation and harmonic frequency up-conversion for the PML-MS DFB laser can be very useful for 60-GHz RoF applications.

References

[1] H. Kurita, T. Shimizu, and H. Yokoyama, "Experimental investigations of harmonic synchronization conditions and mechanisms of mode-locked laser diodes induced by optical-pulse injection," *IEEE J. Sel. Topics Quantum Electron.*, vol. 2, no. 3, pp. 508–513, Sep. 1996.

[2] T. Kuri and K. I. Kitayama, "Long-term stabilized millimeter-wave generation using a high-power mode-locked laser diode module," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 5, pp. 570–574, May 1999.

[3] A. Nirmalathas, H. F. Liu, Z. Ahmed, D. Novak, and Y. Ogawa, "Subharmonic synchronous and hybrid mode-locking of a monolithic DBR laser operating at millimeter-wave frequencies," *IEEE Photon. Technol. Lett.*, vol. 9, no. 4, pp. 434–436, Apr. 1997.

[4] D. Novak, Z. Ahmed, R. B. Waterhouse, and R. S. Tucker, "Signal generation using pulsed smiconductor lasers for application in millimeter-wave wireless links," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2257–2262, Sep. 1995.

[5] M. Attygalle, C. Lim, and A. Nirmalathas, "Dispersion-Tolerant multiple WDM channel millimeter-wave signal generation using a single monolithic mode-locked semiconductor laser," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 295–303, Jan. 2005.

[6] J.-H. Seo, C.-S. Choi, Y.-S. Kang, Y.-D. Chung, J. Kim, and W.-Y. Choi, "SOA-EAM frequency up/down-converters for 60 GHz bi-directional radio-on-fiber systems," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pt. 2, pp. 959–966, Feb. 2006.

[7] Y. A. Leem, D. S. Lee, E. D. Sim, S. B. Kim, D. C. Kim, and K. H. Park, "Self-pulsation in multisection laser diode with a DFB reflector," *IEEE Photon. Technol. Lett.*, vol. 18, no. 4, pp. 622–624, Feb. 15, 2006.

[8] L. A. Johansson, Z. Hu, D. J. Blumenthal, L. A. Coldren, Y. A. Akulova, and G. A. Fish, "40-GHz dual-mode-locked widely tunable sampled-grating DBR laser," *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 285–287, Feb. 2005.

[9] J. S. Lee, H.-J. Song, W. B. Kim, M. Fujise, Y.-H. Kim, and J.-I. Song, "All-optical harmonic frequency upconversion of radio over fiber signal using cross-phase modulation in semiconductor optical amplifier," *Electron. Lett.*, vol. 40, no. 19, pp. 1211–1213, Sep. 2004.

[10] Y. Shoji, K. Hamaguchi, and H. Ogawa, "Millimeter-wave remote self-heterodyne system for extrmely stable and low-cost broadband signal transmission," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 6, pp. 570–574, Jun. 1999.