Harmonic Signal Generation and Frequency Up-Conversion Using a Hybrid Mode-Locked Multisection DFB Laser

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

***Abstract*—Harmonic signal generation and frequency up-conversion are demonstrated using a hybrid mode-locked multisection distributed-feedback (MS-DFB) laser. Hybrid mode-locking is realized by direct injection of electrical local oscillator (LO) signals into the laser gain control section. The harmonic signals are generated when multiple optical modes produced by the hybrid mode-locked MS-DFB laser are detected in a photodiode (PD). In addition, if data signals at f_{IF} are applied to the device along with LO signals at f_{LO}, optical sidebands separated from the optical modes by f_{IF} are generated and harmonic up-converted signals are obtained by mode-beating in PD. Using this method, we demonstrate generation of the third-harmonic millimeter-waves at 30.79 GHz with f_{LO} at 10.263 GHz, and up-conversion of 12.5-Mb/s 32 quadrature amplitude modulation data at 300-MHz f_{IF} into 30-GHz band.**

***Index Terms*—Harmonic signal generation, harmonic up-conversion, hybrid mode-locking (HML), mode-locked multisection distributed-feedback (MS-DFB) lasers.**

I. Introduction

RADIO-OVER-FIBER (RoF) systems, where radio signals are transmitted between central and base stations through optical fiber, have been actively investigated for fixed mobile convergence networks applications due to such advantages of optical fiber as low transmission loss and wide bandwidth [1], [2]. In RoF systems, it is desired that signal generation and frequency up-conversion are done in an optical manner so that simple and cost-effective network configuration is possible [3]–[5]. In addition, it is attractive to use harmonic signals corresponding to the integer multiple of the local oscillator (LO) frequency (f_{LO}) for realization of necessary functions at millimeter (mm)-wave bands because expensive electrical components for mm-waves can be replaced by relatively cheaper ones operating at lower frequency bands.

Monolithic semiconductor mode-locked lasers have been considered as a useful device for harmonic signal generation and frequency up-conversion due to their compactness and stability [6]–[8]. By using a passively mode-locked multisection distributed-feedback (MS-DFB) laser, we previously demonstrated both fourth-harmonic generation of 15.21-GHz f_{LO} and frequency up-conversion of 10-Mb/s quadrature phase-shift keying data at 150 MHz into 60-GHz band [9]. In this demonstration, a synchronous mode-locking (SML) method, where external optical signals modulated at the passive mode-locking (PML) frequency are injected into a passively mode-locked laser, was used for enhancing the stability and quality of the generated signal. However, this scheme requires additional optical components for producing injected optical signals. Moreover, the intermediate frequency (IF) power was very large (larger than 20 dBm in our experiment) for achieving sufficient signal-to-noise ratio (SNR) of the up-converted signal.

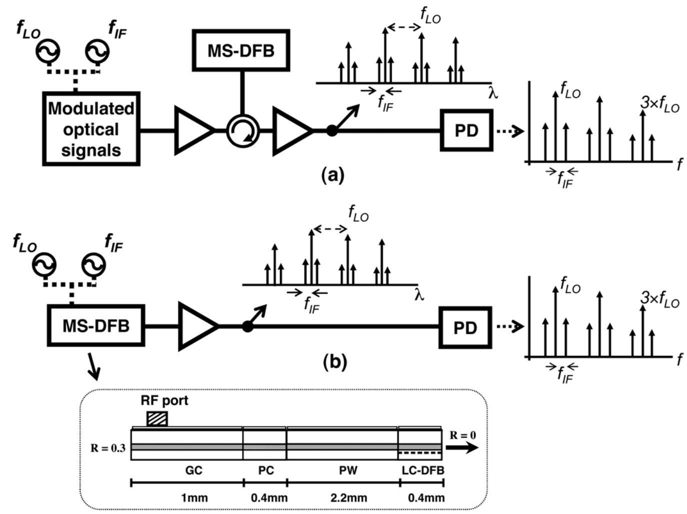

Fig. 1. Schematic diagram for (a) SML and (b) HML. Inset shows the structure of the MS-DFB laser. (- - - : electrical path, —: optical path).

In order to overcome these problems, we added an RF port to the MS-DFB laser so that electrical LO and IF signals can be directly injected into the device, and used a hybrid mode-locking (HML) technique [6], where the electrical LO signal at PML frequency is directly injected to the passively mode-locked laser. Fig. 1(a) and (b) schematically show our previous and new approach, respectively.

In this letter, we demonstrate, using the HML method, generation of the third-harmonic mm-wave at 30.79 GHz with f_{LO} of 10.263 GHz and up-conversion of 12.5-Mb/s 32 quadrature amplitude modulation (QAM) data at 300-MHz f_{IF} into the 30-GHz band. We show that our approach based on the HML

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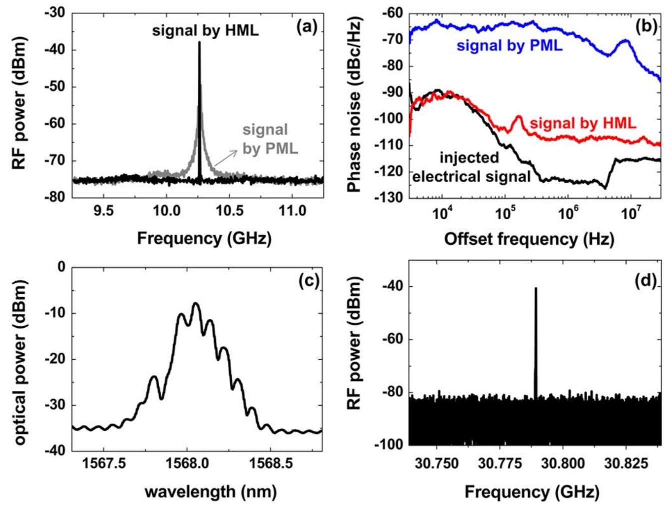

Fig. 2. (a) Measured RF spectra of the obtained signals by PML and HML. (b) Measured phase noises of achieved signals by PML and HML, and injected electrical signals. (c) Optical spectrum of the hybrid mode-locked MS-DFB laser. (d) Measured third-harmonic component.

method is simpler and requires much less IF power compared to the SML method.

II. Operating Principle

The structure of the laser used for this investigation is shown in the inset of Fig. 1. As can be seen in the figure, the MS-DFB laser consists of loss-coupled DFB (LC-DFB), passive waveguide, phase control (PC), and gain control (GC) sections, and an RF port is attached to the GC section. Details of the device structure can be found in [10]. The device used for our present investigation is optimized for the PML frequency of about 10 GHz whereas the device used in our previous investigation was for 15 GHz.

HML can be realized by direct injection of the electrical LO signal at f_{LO} to the GC section of the MS-DFB laser when the laser is passively mode-locked with proper bias conditions [9], [10]. Once HML is achieved, the laser can produce phase-correlated multiple optical modes separated by f_{LO}, and when they are detected by a photodiode (PD), low phase-noise harmonic signals are generated. Moreover, if data signals carried at f_{IF} are simultaneously applied to the GC section, multiple laser modes are modulated by f_{IF} resulting in optical sidebands separated by f_{IF}. When these optical signals are detected by PD, electrical sidebands are generated around $n \times f_{\mathrm{LO}}$ separated by f_{IF}, as shown in Fig. 1(b). In other words, data signals at f_{IF} are frequency up-converted to the nth harmonic band of f_{LO} by the hybrid mode-locked MS-DFB laser. For the present investigation, we are interested in the third-harmonic signals around 30-GHz band.

III. Experimental Results

Fig. 2(a) shows measured RF spectra obtained by PML and HML. For PML, the MS-DFB laser was biased at $I_{\mathrm{LC-DFB}} = 47.47$ mA, $I_{\mathrm{PC}} = 10$ mA, and $I_{\mathrm{GC}} = 80$ mA, resulting in oscillation at $f_{\mathrm{LO}} = 10.263$ GHz. For HML, the 20-dBm electrical signal at $f_{\mathrm{LO}} = 10.263$ GHz was directly injected into GC section. As shown in Fig. 2(a), HML significantly narrows the spectrum linewidth. Fig. 2(b) shows measured phase noise spectra for PML and HML. The measured phase noise at 100-kHz frequency offset is -64.33 dBc/Hz for PML and -103.33 dBc/Hz for HML. Clearly, HML drastically enhances the phase quality. The optical spectrum of the hybrid mode-locked MS-DFB laser is shown in Fig. 2(c) and many optical modes in the optical spectrum can generate harmonic signals corresponding to the integer multiple of f_{LO} by mode-beating in PD. The optical modulation index for the third-harmonic signal estimated from the optical spectrum is about 51.5%. Fig. 2(d) shows the measured RF spectrum of the third-harmonic signal at the received optical power of about 2.6 dBm. Since the generated third-harmonic signal power was about -40.6 dBm, the harmonic power efficiency, defined as the power ratio between the injected RF signal (20 dBm) for HML and the generated third-harmonic signal, is about -60.6 dB. The fundamental and second-harmonic signals are also generated and their power (and the power efficiency) was about -28.7 dBm (-48.7 dB) and -33.5 dBm (-53.5 dB), respectively. The difference of about 12 dB in the RF power efficiency between fundamental and third-harmonic signals causes optical power penalty of about 6 dB induced by the third-harmonic up-conversion.

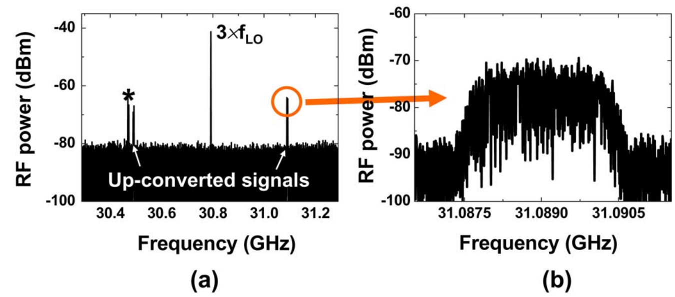

Fig. 3. (a) Measured RF spectrum of up-converted double sideband signals of 12.5-Mb/s 32 QAM data carried at 300 MHz. (b) Magnified upper sideband (USB) up-converted signal.

For the demonstration of harmonic frequency up-conversion, both 12.5-Mb/s 32 QAM data at f_{IF} of 300 MHz, which is within the IF bandwidth of about 600 MHz, and f_{LO} were injected into the GC section of the passively mode-locked MS-DFB laser. The applied IF power was -16 dBm. RF spectrum of the third-harmonic up-converted data signals is shown in Fig. 3(a). The spectrum clearly shows up-converted double sideband data signals at f_{IF} (300 MHz) away from $3 \times f_{\mathrm{LO}}$ (30.79 GHz). In Fig. 3(a), the peak marked with "$*$" is an image signal produced by the external harmonic mixer (HP11970) used for the measurement. Fig. 3(b) shows the magnified upper sideband up-converted data spectrum.

For evaluation of harmonic up-converted signal quality, up-converted data were analyzed by Agilent 89441A vector signal analyzer after frequency down-conversion with an external mixer and a 30-GHz LO. Fig. 4(a) and (b) show the constellation and the eye diagram for demodulated 12.5-Mb/s 32 QAM signal, respectively. The eye was clearly open and the measured error vector magnitude was about 4.3% corresponding to the estimated SNR of 23.3 dB. Much higher SNR was achieved compared to the SML MS-DFB laser (SNR of about 16 dB) with much lower IF power (-16 dBm versus

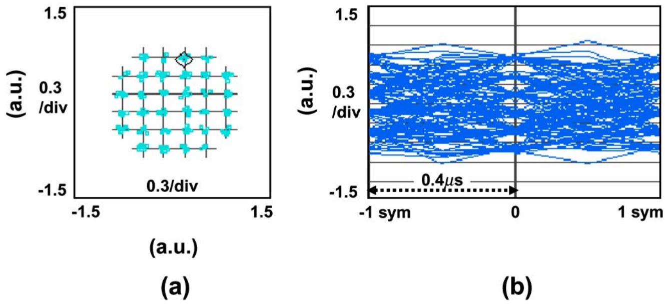

Fig. 4. Measured (a) constellation and (b) eye diagram of the demodulated 12.5-Mb/s 32 QAM data.

20 dBm) because direct current modulation provides much higher modulation efficiency.

IV. Conclusion

We demonstrated harmonic signal generation and harmonic frequency up-conversion using a hybrid mode-locked MS-DFB laser with direct injection of electrical LO and IF signals into the GC section of the device. Using the device, we successfully generated mm-waves corresponding to the third-harmonic (30.79 GHz) component of $f_{\rm LO} = 10.263$ GHz. In addition, we achieved harmonic up-conversion of 12.5-Mb/s 32 QAM data carried at 300 MHz into the 30-GHz band. Compared to our previous results achieved with the synchronously mode-locked MS-DFB laser, this new scheme produces much higher SNR with much lower IF power and requires less optical components.

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