1.244-Gb/s Data Distribution in 60-GHz Remote Optical Frequency Up-Conversion Systems

Jun-Hyuk Seo, Young-Kwang Seo, and Woo-Young Choi

***Abstract*—We experimentally demonstrate 63-GHz 1.244-Gb/s radio-on-fiber downlink data distribution using the remote optical frequency up-conversion technique. Sixty-three-gigahertz optical heterodyne local oscillator signals are cross-gain modulated by optical baseband signals inside a semiconductor optical amplifier. After photodetection, frequency up-converted signals at 63 GHz are generated. The bit-error-rate performance is investigated as a function of optical baseband signal power in a wide wavelength range.**

***Index Terms*—Microwave photonics, millimeter-wave frequency conversion, millimeter-wave radio communication, radio-on-fiber (RoF) systems, semiconductor optical amplifier (SOA).**

I. Introduction

SIXTY-GIGAHERTZ wireless systems are attracting research interest for future broadband multimedia services, wireless interconnection of backbone networks, and wireless local area network and wireless personal area network services [1], [2]. The reason is that high directivity and high oxygen absorption loss of 60-GHz signals are useful for these system applications. In addition, the license-free wide bandwidth in the 60-GHz band is very attractive [1], [2]. However, the implementation cost of 60-GHz systems is still very high, and radio-on-fiber (RoF) technology can alleviate this problem. In RoF systems, expensive system equipment can be centralized and many base stations can be controlled by a single central office, resulting in overall cost reduction. Moreover, data transmission based on low-loss fiber can extend service areas [3]–[5]. There are many techniques to realize low-cost RoF systems, and recently, transmission of gigabit data using RoF systems have been reported [4], [5]. Optical mixing schemes using semiconductor optical amplifiers (SOAs) are attractive because of their high conversion efficiency [6]–[9]. We have previously proposed a remote optical frequency up-conversion method using an SOA and a photodiode (PD) for downlink data distribution [8], [9]. Fig. 1 schematically shows this method. When optical heterodyne local oscillator (LO) signals at λ_{LO} along with optical signals at λ_{IF} carrying intermediate frequency (IF) signals are injected into SOA, optical heterodyne LO signals are cross-gain modulated by IF signals, and frequency up-converted signals at f_{LO} are generated by the beating process in a PD.

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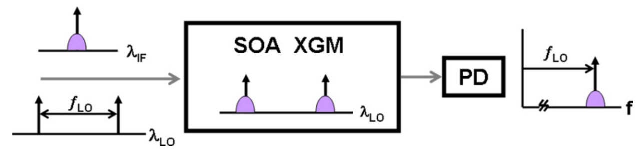

Fig. 1. Operation schematic of SOA-PD frequency up-converter. (Color version available online at http://ieeexplore.ieee.org.)

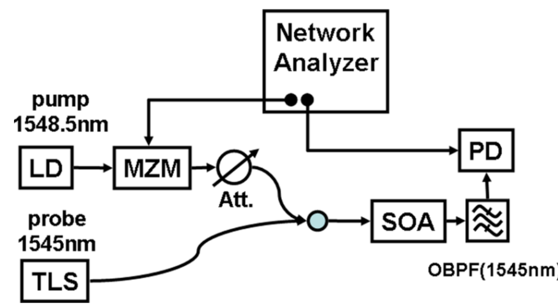

Fig. 2. Measurement setup for SOA XGM frequency response. OBPF: optical bandpass filter. LD: laser diode. TLS: tunable laser source. MZM: Mach–Zehnder modulator. (Color version available online at http://ieeexplore.ieee.org.)

In this letter, we present measurement results of the SOA cross-gain modulation (XGM) bandwidth to validate the wide-bandwidth mixing operation and experimentally demonstrate error-free 1.244-Gb/s amplitude shift-keying (ASK) data transmission at 63 GHz. For the frequency up-conversion experiment, 63-GHz optical heterodyne LO signals and 1.244-Gb/s optical baseband signals are used. The dependence of bit-error rates (BERs) on optical baseband signal power in a wide wavelength range is also investigated.

II. Measurement of SOA XGM Response

In our frequency up-conversion scheme, the SOA XGM bandwidth is an important parameter. Since LO frequency is usually beyond the SOA XGM bandwidth, optical LO signals themselves do not cause any significant XGM. However, when data and/or IF signals are within the XGM bandwidth, they can cross-gain modulate each of optical heterodyne LO modes, resulting in frequency up-conversion after beating in a PD [8]. Consequently, the XGM bandwidth limits data and/or IF frequencies that can be frequency up-converted. We have previously reported that the theoretical bandwidth of our frequency up-conversion method can be several gigahertz [9], which we verify with the frequency response measurement of SOA XGM.

Fig. 2 shows the experimental setup to measure SOA XGM frequency response. For a pump signal, a 1548.5-nm distributed feedback laser and a Mach–Zehnder modulator having 3-dB bandwidth of 8 GHz were used, and for a probe signal, a 1545-nm

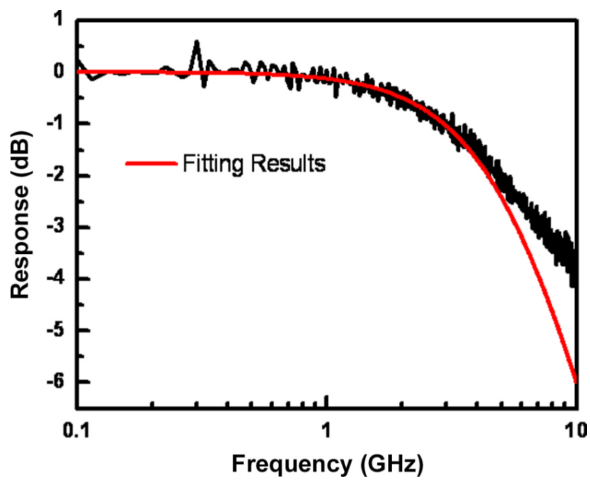

Fig. 3. Frequency response for SOA XGM for a −12-dBm SOA input pump signal power. (Color version available online at http://ieeexplore.ieee.org.)

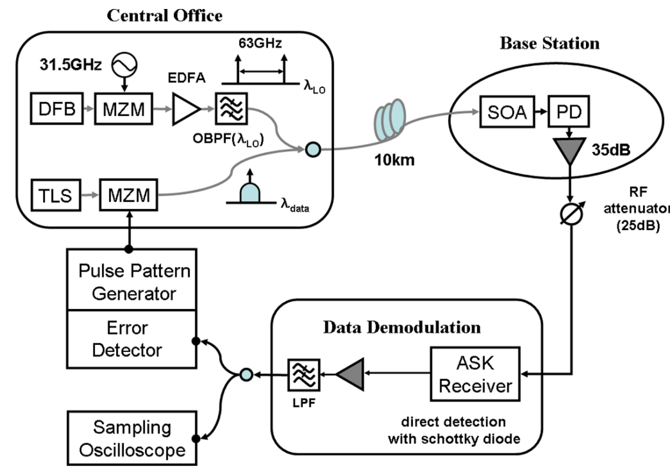

Fig. 4. Experimental setup for 1.244-Gb/s 63-GHz RoF downlink data transmission. EDFA: erbium-doped fiber amplifier. LPF: lowpass filter. (Color version available online at http://ieeexplore.ieee.org.)

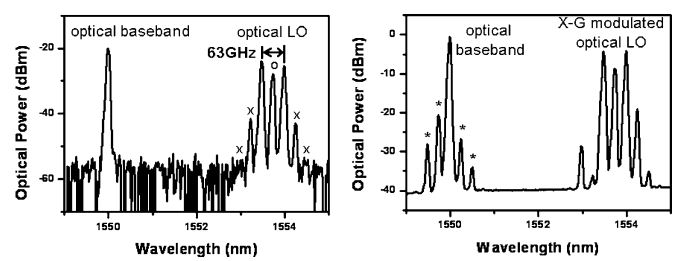

Fig. 5. Optical spectrum of downlink optical LO and data signals (a) before SOA and (b) after SOA.

continuous-wave light source was used. An optical bandpass filter was placed before a PD having 15-GHz bandwidth to block the pump source. The SOA was biased at 200 mA, at which condition the optical gain and saturation output power at 1550 nm was 29 dB and 9 dBm, respectively. Before XGM frequency response measurement, the frequency response of the pump signal was measured for calibration. The frequency responses were measured with a 13.5-GHz network analyzer. The SOA input power of the probe signal was fixed at −30 dBm, and the power of pump signals was varied from −30 to −12 dBm. Fig. 3 shows the normalized frequency response for −12-dBm pump signal and the fitted results with the double-pole system response as reported in [9]. Discrepancies between measured and fitted data at high frequencies are believed due to the incomplete SOA model. A 3-dB bandwidth was extracted from the fitted results. For −30-dBm pump signals, 3-dB bandwidth is 4.2 GHz, and for −20- and −12-dBm signals, 3-dB bandwidth is 4.5 and 5.8 GHz, respectively, which are sufficient for gigabit data transmission using our frequency up-conversion scheme. The reason for 3-dB bandwidth increase with the pump signal power is that XGM speed is limited by the effective carrier recombination rate, γ_{eff}, in SOA as shown below [9]

$$f_{3\text{ dB}} \propto \gamma_{\text{eff}} = \frac{1}{\tau_S} + \frac{1}{\tau_{\text{pump}}} + \frac{1}{\tau_{\text{probe}}} \tag{1}$$

where τ_s is spontaneous carrier lifetime in SOA, $\tau_{\text{pump,probe}}$ is stimulated recombination lifetime for optical pump or probe signals. Since τ_{pump} is inversely proportional to the SOA input pump signal power, the increase in pump signal power increases γ_{eff}, resulting in XGM bandwidth increase.

III. Data Transmission Experiments and Results

Fig. 4 shows the experimental setup for 60-GHz band RoF systems using our frequency up-converter. The 63-GHz optical heterodyne LO signals at 1553.3 nm were generated using a double-sideband suppressed carrier (DSB-SC) method, for which a 40-GHz Mach–Zehnder modulator was biased at the minimum transmission condition, and modulated by 31.5-GHz RF signals. An erbium-doped fiber amplifier was used to increase heterodyne optical LO power along with an optical bandpass filter having about 0.4-nm passband for amplifier noise reduction. For data signals, another wavelength optical signal was externally modulated by 2-V peak-to-peak 1.244-Gb/s non-return-to-zero pseudorandom bit sequences having a pattern length of $2^{15} - 1$. These two optical signals were combined, and then transmitted to the base station via 10-km optical fiber. Fig. 5(a) shows the spectrum of optical heterodyne LO signals at 1553.3 nm and baseband data signals at 1550 nm before SOA. The peak at 1553.3 nm marked with “o” is due to incomplete carrier suppression with DSB-SC generation and peaks marked with “x” are harmonics of 31.5-GHz modulation.

At the base station, two optical signals were injected into SOA, and optical heterodyne signals were cross-gain modulated by optical baseband signals. The SOA was biased at 150 mA, which gave 25-dB optical gain and 8-dBm output saturation power. Fig. 5(b) shows the optical spectrum after SOA, and these signals were photodetected by a 60-GHz broadband PD. In Fig. 5(b), spurious peaks marked with asterisks around 1550 nm are the result of optical heterodyne signals cross-gain modulating the optical baseband signal. However, their effects are negligible to the link performance, because 31.5-GHz signals resulting from the photodetection of spurious peaks are far off from 63-GHz data signals, and their harmonics are very low, as shown in the Fig. 5(b). Fig. 6(a) shows the frequency up-converted RF spectrum of 1.244-Gb/s data at 63 GHz. In this measurement, the optical LO power before SOA was −13 dBm, and the optical baseband signal power and wavelength was −13 dBm and 1550 nm, respectively. As shown in the figure, baseband data signals are successfully up-converted to 63 GHz. The peaks

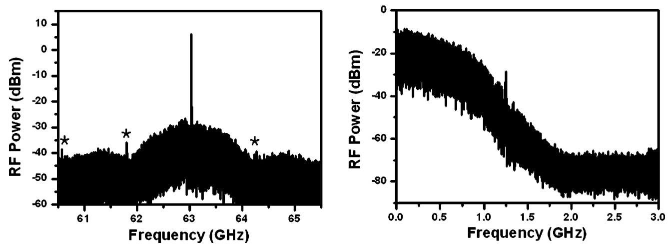

Fig. 6. (a) RF spectrum of frequency up-converted 63-GHz data signals and (b) demodulated baseband signals. Resolution bandwidth for both spectra is 1 MHz.

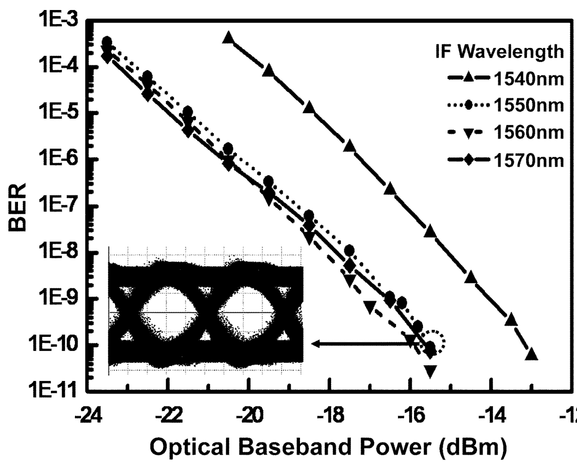

Fig. 7. Dependence of BER performance on SOA input optical baseband signal power. Data wavelength was changed from 1540 to 1570 nm.

marked with asterisks having 1.244-GHz separation appear because baseband data are ASK modulated. The center peak at 63 GHz due to optical LO signals can saturate amplifiers and limit output data signal power at the base station. Other modulation techniques using antipodal signals and LO rejection filtering at 60-GHz band can avoid this problem.

To demodulate 63-GHz ASK data signals, a commercially available direct conversion demodulator based on a Schottky diode was used. In this demodulator, input 63-GHz data signals are recovered at baseband due to square-law detection characteristics of the Schottky diode. The data signal was attenuated by 25 dB since the demodulator that we used has a maximum power limit of -30 dBm. Fig. 6(b) shows the RF spectrum of 1.244-Gb/s baseband data. After baseband amplification and additional low pass filtering of data signals, demodulated data signals were analyzed by a sampling oscilloscope for eye diagram measurement, and an error detector for BER measurement. Fig. 7 shows the measured BER as a function of the optical baseband signal power before SOA at several different wavelengths varying from 1540 to 1570 nm. The optical baseband signal power before SOA influences frequency conversion efficiency affecting signal-to-noise ratios (SNRs), but the optical power after SOA does not change very much due to SOA gain saturation. For this measurement, optical LO signal power before SOA was fixed at -13 dBm. As can be seen in Fig. 7, the BER decreases as optical baseband signal power increases. The increased optical data signal power before SOA can improve XGM efficiency in SOA, which results in SNR improvement. In the wavelength range from 1550 to 1570 nm, the power penalty for 10^{-9} BER is less than 1 dB. The eye diagram for error-free conditions at 1550-nm data signals is also shown in Fig. 7. However, the power penalty for the 1540-nm wavelength signal is about 2.5 dB. The unsaturated gain spectrum of the SOA used in our study has a peak at around 1550 nm. But the SOA gain peak shifts to a longer wavelength due to the carrier depletion when the SOA gain is saturated. Therefore, frequency up-conversion efficiency is higher for wavelengths longer than 1550 nm [9]. For shorter wavelength signals, large power penalties occur due to low frequency up-conversion efficiency. Nevertheless, error-free data transmission is accomplished for a wide range of data wavelengths proving that wavelength-division-multiplexing data transmission is possible with our scheme. It is believed that with further optimization of data modulation and demodulation, and optimization of SOA characteristics, the transmission performance can be further improved.

IV. Conclusion

We experimentally demonstrated error-free 1.244-Gb/s ASK data transmission based on remote frequency up-conversion using SOA XGM in 63-GHz RoF systems. The frequency response of the frequency up-converter was measured to show the operation bandwidth. Sixty-three-gigahertz optical heterodyne LO signals were cross-gain modulated by the 1.244-Gb/s optical baseband signals, and frequency up-converted 63-GHz signals were generated after photodetection. The dependence of BERs on optical baseband signal power and wavelength before SOA was investigated. The BER performance was improved with the increase of input optical power due to increased conversion efficiency, and error-free data transmission was achieved in a wide wavelength range. With these, we verified that the frequency up-conversion technique has enough bandwidth for gigabit-level data transmission in 60-GHz band for a wide range of data wavelengths.

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