SOA–EAM Frequency Up/Down-Converters for 60-GHz Bi-Directional Radio-on-Fiber Systems

Jun-Hyuk Seo, Chang-Soon Choi, Young-Shik Kang, Yong-Duck Chung, Jeha Kim, and Woo-Young Choi

***Abstract*—We investigate a frequency up/down-converter based on a single cascaded semiconductor optical amplifier (SOA)-electroabsorption modulator (EAM) configuration for bi-directional 60-GHz-band radio-on-fiber (RoF) system applications. SOA cross-gain modulation and photodetection in EAM are used for frequency up-conversion, and EAM nonlinearity is used for frequency down-conversion. In our scheme, both 60-GHz local-oscillator (LO) signals and IF signals are optically transmitted from a central station to base stations. We characterize the dependence of frequency up/down-conversion efficiencies on EAM bias and optical LO power. For frequency up-conversion, maximum conversion gain of approximately 8 dB was obtained and, for frequency down-conversion, more than approximately 18-dB conversion loss was measured. Utilizing this frequency up/down converter, we demonstrate a 60-GHz bi-directional RoF link. Optically transmitted downlink 10-Mb/s quadrature phase-shift keying (QPSK) data at 100-MHz IF are frequency up-converted to the 60-GHz band at the base station, and uplink 10-Mb/s QPSK data in the 60-GHz band are frequency down-converted to 150-MHz IF and transmitted to the central station. In addition, the dependence of error vector magnitudes on IF signal power and wavelength is investigated.**

***Index Terms*—Electroabsorption modulator (EAM), frequency conversion, millimeter-wave communication, optical mixers, optical modulation, radio-on-fiber (RoF) system, semiconductor optical amplifier (SOA).**

I. INTRODUCTION

MILLIMETER-WAVE bands have been actively investigated for future broad-band wireless communication systems. 60-GHz band, available as an unlicensed band, is attracting much attention due to wide bandwidth, frequency reusability, and high directivity [1], [2]. However, the high free-space propagation loss of 60-GHz signals demands many base stations covering small-sized cells. Consequently, simple and cost-effective base-station design becomes very important for realizing 60-GHz wireless systems. As one solution, radio-on-fiber (RoF) systems are actively investigated. In RoF systems, radio signals are optically transmitted between central and base stations, resulting in low-loss transmission of radio signals and realization of simple base stations [3]–[5].

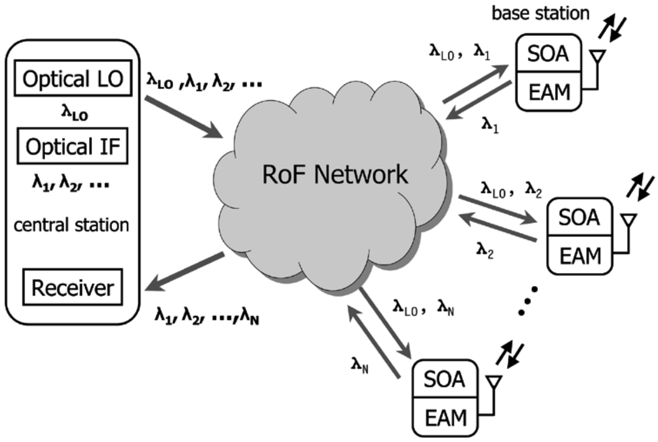

Fig. 1. RoF system schematic using SOA–EAM frequency converters.

However, the single-mode fiber transmission of optically intensity-modulated millimeter-wave signals can suffer severe signal fading due to fiber chromatic dispersion [6]. Various techniques for dispersion-insensitive transmission of millimeter-wave signals have been proposed using dispersion-compensation techniques [7], [8] and remote frequency-conversion techniques [3], [9]. The dispersion-compensation techniques are sensitive to fiber transmission distance and optical signal wavelength and, as a result, RoF systems need many adaptable dispersion compensators, making system design difficult. In remote frequency-conversion techniques, IF signals are optically transmitted between central and base stations, and frequency up-conversion to and down-conversion from the millimeter-wave band occur at the base station. Since fiber transmission of low-frequency signals in the form of IF signals is hardly affected by dispersion, frequency conversion at the remote base stations can be a simple solution for the dispersion-induced signal-fading problem. However, expensive millimeter-wave-band oscillators and mixers are needed for remote frequency conversion, which makes the base stations complex and expensive. To solve this problem, optical frequency-conversion techniques can be used [10]–[14] in which data carried in IF signals are frequency up- and down-converted at the base station with the help of dispersion-insensitive optical millimeter-wave signals generated at the central station by an optical heterodyne technique or optical single-sideband modulation technique. Consequently, there is no need for expensive electrical oscillators and mixers at the base station, allowing simple and cost-effective base-station architecture.

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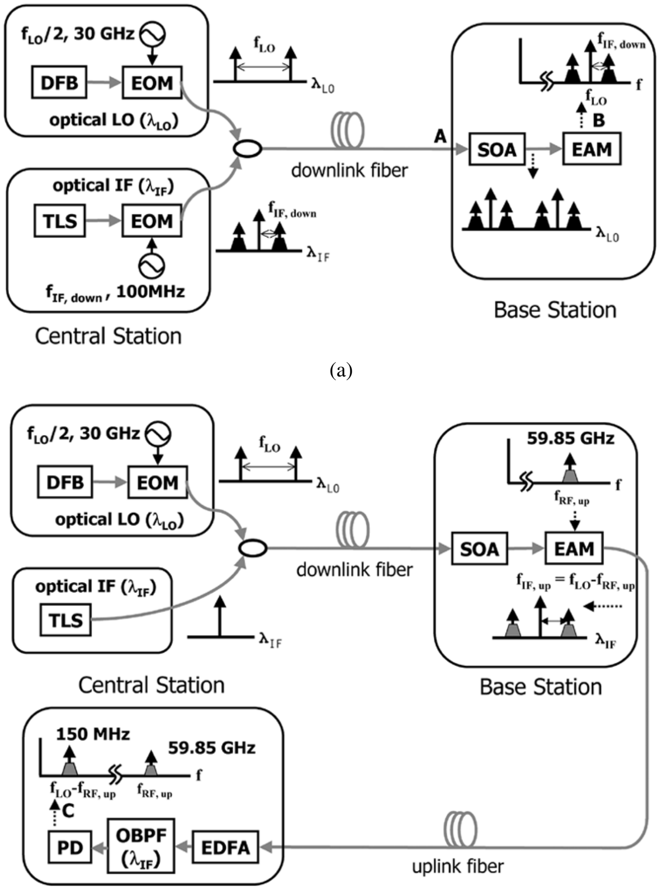
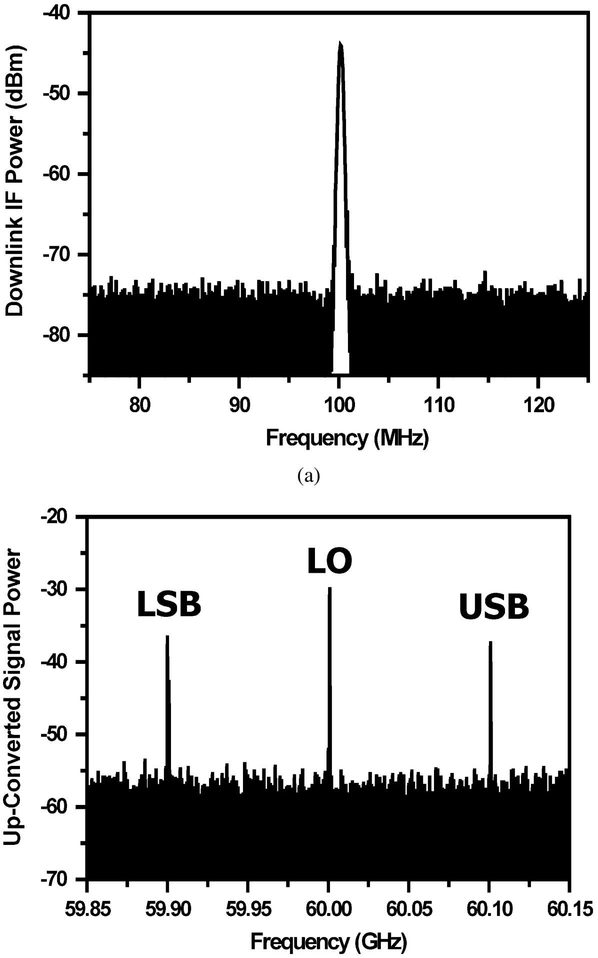


(a)

(b)

Fig. 2. Schematics for: (a) frequency up-conversion and (b) frequency down-conversion processes and experimental setup used for verification. Tunable laser source (TLS), electrooptic modulator (EOM), erbium-doped fiber amplifier (EDFA), optical bandpass filter (OBPF), photodetector (PD).



(a)

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Fig. 3. RF spectra for downlink frequency up-conversion. (a) IF signals without SOA. (b) Frequency up-converted signals. The resolution bandwidth was 300 kHz for (a) and 100 kHz for (b). A 17-dB gain electrical amplifier was used for (b). Lower sideband (LSB), local oscillator (LO), upper sideband (USB).

In this paper, we investigate a 60-GHz optical frequency converter, which performs frequency up-conversion and frequency down-conversion at the remote base station based on a cascaded semiconductor optical amplifier (SOA)–electroabsorption modulator (EAM) configuration. SOA cross-gain modulation and photodetection in an EAM are used for frequency up-conversion, and EAM nonlinearity is used for frequency down-conversion. Both local-oscillator (LO) and IF signals for frequency conversion are optically provided by the central station. Therefore, a simple base station having only one cascaded SOA–EAM configuration can be realized. Moreover, since optical LO signals are separated from optical IF signals, optical LO signals can be shared among several base stations and wavelength-division multiplexing (WDM) techniques can be applied for accessing different base stations with different IF wavelengths. Fig. 1 shows the bi-directional RoF system where such SOA–EAM frequency converters are used.

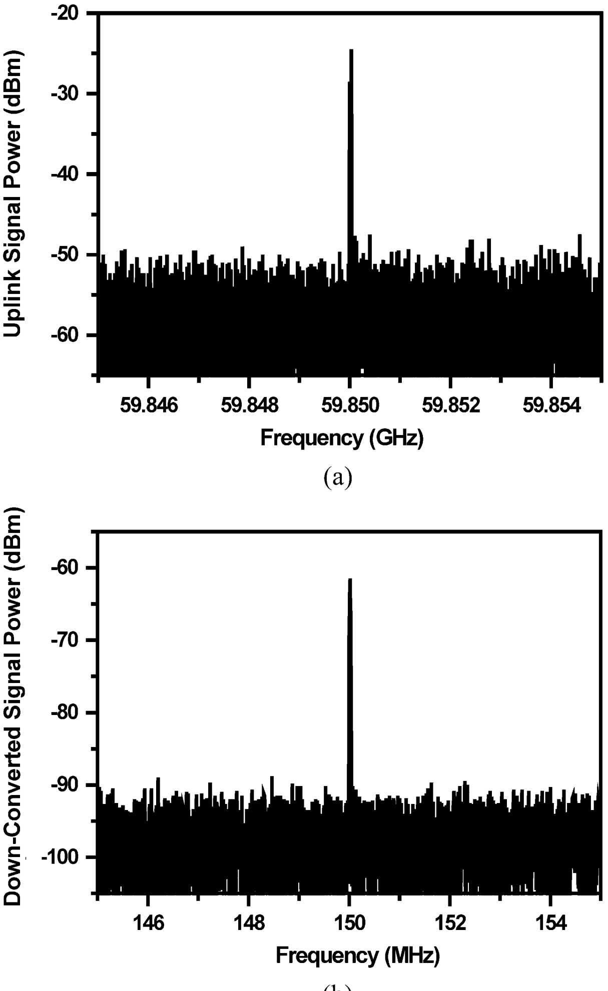
We also investigate frequency-conversion efficiencies as functions of EAM bias and optical LO signal power. For bi-directional 60-GHz RoF system demonstration, downlink 10-Mb/s quadrature phase-shift keying (QPSK) data at 100-MHz IF are transmitted to the base station and frequency up-converted to the 60-GHz band, and uplink QPSK data in the 60-GHz band are frequency down-converted to 150-MHz IF and optically transmitted to the central station. By measuring error vector magnitudes (EVMs), error-free data transmission in both directions is verified, and system performance dependence on power and wavelength of optical IF signals is investigated.

II. OPERATION PRINCIPLES OF FREQUENCY CONVERTERS

Fig. 2(a) and (b) schematically shows operation principles of frequency up- and down-conversion using the SOA–EAM configuration, respectively.

A. Frequency Up-Conversion for Downlink Transmission

For frequency up-conversion, optical LO at λ_{LO} having two optical modes separated by f_{LO} and optical IF at λ_{IF} having two sidebands separated from the carrier by $f_{\mathrm{IF,down}}$ are transmitted from the central station and injected into the SOA in the base station. Inside the SOA, two modes of an optical LO are cross-gain modulated by optical IF signals. After photodetection in the EAM, frequency up-converted signals at $f_{\mathrm{LO}} \pm f_{\mathrm{IF,down}}$ are obtained as square-law beating products. This frequency up-conversion process is similar to that in the SOA–PD configuration



(a)

(b)

Fig. 4. RF spectra for uplink frequency down-conversion. (a) RF signals measured at the central station. (b) Frequency down-converted signals measured at the central station. The resolution bandwidth was 1 kHz for both. A 17-dB gain electrical amplifier was used for (a) and a 20-dB gain electrical amplifier was used for (b).

reported in [14] and [15]. In order to verify frequency up-conversion, the experimental setup shown in Fig. 2(a) was used. 60-GHz optical heterodyne LO signals were generated by modulation of a Mach–Zehnder modulator biased at the minimum transmission point (V_π) with 30-GHz signals. The wavelength of the optical LO was 1553.3 nm and its power measured before the SOA was -15 dBm. Optical IF signals were generated by modulation of another Mach–Zehnder modulator biased at the quadrature point with 100-MHz 10-dBm RF signals. The wavelength of optical IF can be any wavelength within the SOA gain bandwidth [14]. For the experiment, optical IF wavelength was 1550 nm and its power measured before the SOA was -8 dBm. The SOA bias current was 150 mA, which provided the SOA gain of 25 dB and saturation output power of 7 dBm. The EAM used in the experiment was designed and packaged for 60-GHz narrow-band operation [16] and biased at -2.5 V. Fig. 3(a) and (b) shows the resulting RF spectra of downlink IF signals at 100 MHz without an SOA [measured at Point A in Fig. 2(a)] and frequency up-converted 60-GHz-band signals [measured at Point B in Fig. 2(a)], respectively. They clearly show frequency up-converted signals at 59.9 GHz ($f_{\mathrm{LO}} - f_{\mathrm{IF,down}}$) and 60.1 GHz ($f_{\mathrm{LO}} + f_{\mathrm{IF,down}}$).

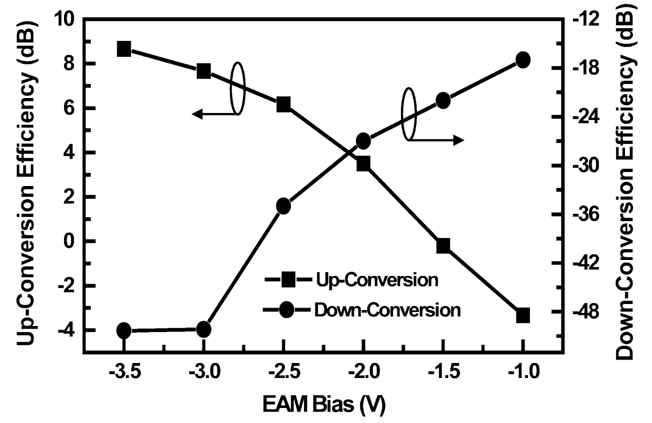
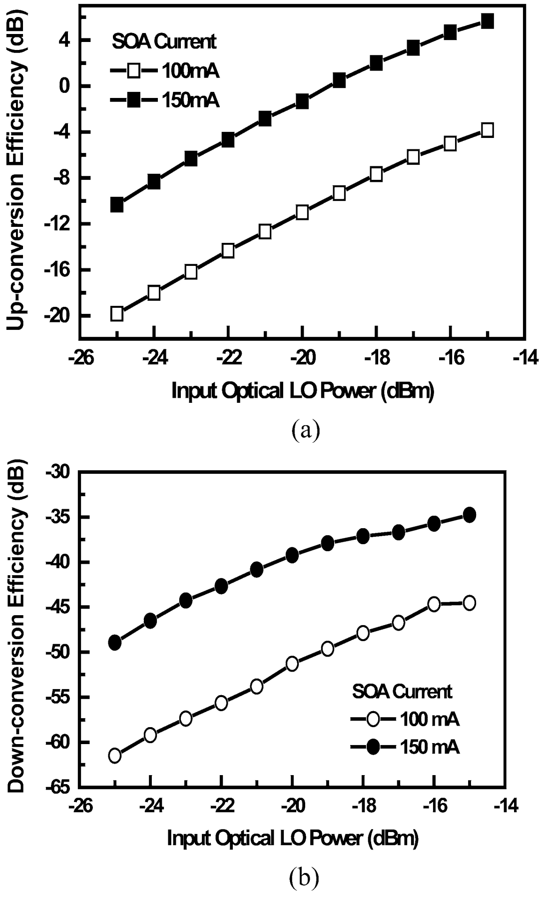


Fig. 5. Frequency up- and down-conversion efficiencies (η_{up}, and η_{down}) as a function of EAM bias.



(a)

(b)

Fig. 6. (a) Frequency up-conversion efficiency (η_{up}) and (b) frequency down-conversion efficiency (η_{down}) as a function of optical LO signal power. Optical LO power was measured in front of SOA.

B. Frequency Down-Conversion for Uplink Transmission

For frequency down-conversion, an optical LO and optical IF are injected into the SOA–EAM configuration. During the photodetection process in the EAM, signals having f_{LO} component are generated inside the EAM. These signals are frequency mixed with RF signals ($f_{\mathrm{RF,up}}$) externally applied to the EAM due to EAM nonlinearity, causing frequency down-conversion to $f_{\mathrm{IF,up}} = f_{\mathrm{LO}} - f_{\mathrm{RF,up}}$. The resulting $f_{\mathrm{IF,up}}$ signals then modulate optical IF signals at λ_{IF} in the same EAM, which are then

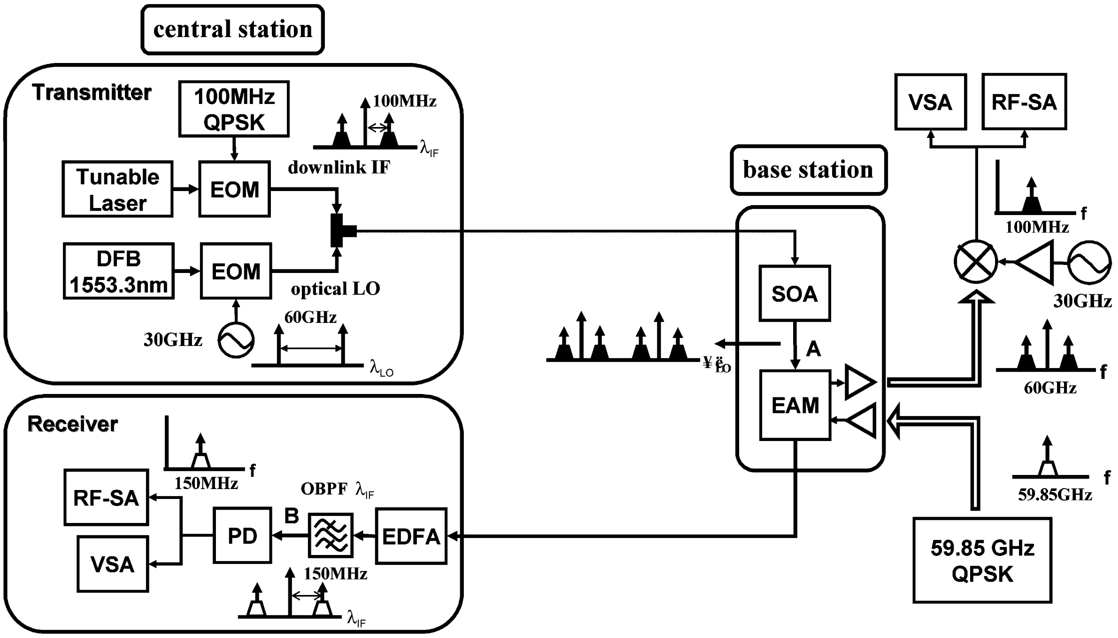


Fig. 7. Experimental setup for 60-GHz bi-directional RoF systems. Electrooptic modulator (EOM), vector signal analyzer (VSA), RF-spectrum analyzer (RF-SA), erbium-doped fiber amplifier (EDFA), (PD) photodetector.

sent back to the central station. This frequency down-conversion method was reported previously in [17] and [18]. However, with addition of the SOA, as in our scheme, both frequency up- and down-conversion are possible and optical amplification by the SOA results in better uplink performance. Moreover, the EAM and SOA can be monolithically integrated [19], making the frequency converter more compact. Although the same optical IF are used for both downlink and uplink, this is not a problem since $f_{\mathrm{IF,down}}$ and $f_{\mathrm{IF,up}}$ are not the same and can be easily separated electronically. In this frequency converter, the EAM is acting as a multifunctional device, which simultaneously performs photo-detection, frequency down-conversion, and uplink optical IF signal modulation. Consequently, the antenna base station can be greatly simplified.

The setup shown in Fig. 2(b) was used for the frequency down-conversion experiment. An optical LO was generated with the same method used for frequency up-conversion, and an optical IF was supplied from a tunable light source. In this experiment, the optical IF did not include $f_{\mathrm{IF,down}}$ so that only frequency down-conversion characteristics for uplink can be investigated. 10-dBm 59.85-GHz signals were used as uplink RF signals, which were applied to the EAM biased at -2.5 V. Inside the EAM, 59.85-GHz signals were mixed with 60-GHz signals produced by photodetection of optical LO and produced $f_{\mathrm{IF,up}} = 150$-MHz signals, which then modulated the optical IF. The uplink optical IF signals were transmitted to the central station, and photodetected after optical amplification. An optical bandpass filter having a λ_{IF} passband was inserted before the photodetector in order to block optical LO signals at λ_{LO} delivered to the central station. This filtering is necessary because optical LO signals modulated by uplink RF signals can produce interfering frequency down-converted signals at the central station [13]. Fig. 4(a) and (b), respectively, shows the RF spectra of uplink RF signals at 59.85 GHz and frequency down-converted IF signals at 150 MHz measured simultaneously at the central station [measured at Point C in Fig. 2(b)]. Uplink RF signals are delivered to the central station at λ_{IF} because the EAM is modulated with both uplink RF signals and frequency down-converted IF signals.

III. CONVERSION EFFICIENCY OF SOA–EAM FREQUENCY CONVERTER

Since the mixer conversion efficiency is one of the important parameters for RF system design [20], we investigated conversion efficiency of the SOA–EAM frequency converter. The conventional definition of mixer conversion efficiency is the ratio of input signal power to frequency-converted output signal power. However, it is very difficult to directly apply this definition to our frequency converter because it is difficult to measure exact signal powers related to frequency up/down-conversion due to many optical components used in the experiment. For our purpose, we define up-conversion efficiency (η_{up}) as the ratio of EAM photodetected frequency up-converted signal power to the EAM photodetected IF signal power. For example, the ratio of lower sideband power in Fig. 3(b) to peak power in Fig. 3(a) is η_{up}. The frequency down-conversion efficiency (η_{down}) is defined as the ratio of frequency down-converted signal power to uplink RF signal power measured at the central station simultaneously. For example, the ratio of peak power in Fig. 4(b) to peak power in Fig. 4(a) is η_{down}. As explained in Section II, the frequency down-conversion process is a complex one involving photodetection, mixing, and modulation. By comparing $f_{\mathrm{IF,up}}$ and $f_{\mathrm{RF,up}}$ delivered at λ_{IF} to the central station, the influence of EAM modulation efficiency can be eliminated, and internal mixing efficiency of the EAM can be estimated.

The same experimental setup shown in Fig. 2 was used for conversion-efficiency measurement. The 16-dB difference in the EAM photodetection response between 100 MHz–60 GHz was corrected for η_{up} calculation. The 5-dB difference in photodiode response between 150 MHz–60 GHz was also corrected for η_{down} calculation. In addition, the different electrical gains were corrected for both η_{up} and η_{down}. The measurement was performed in back-to-back condition.

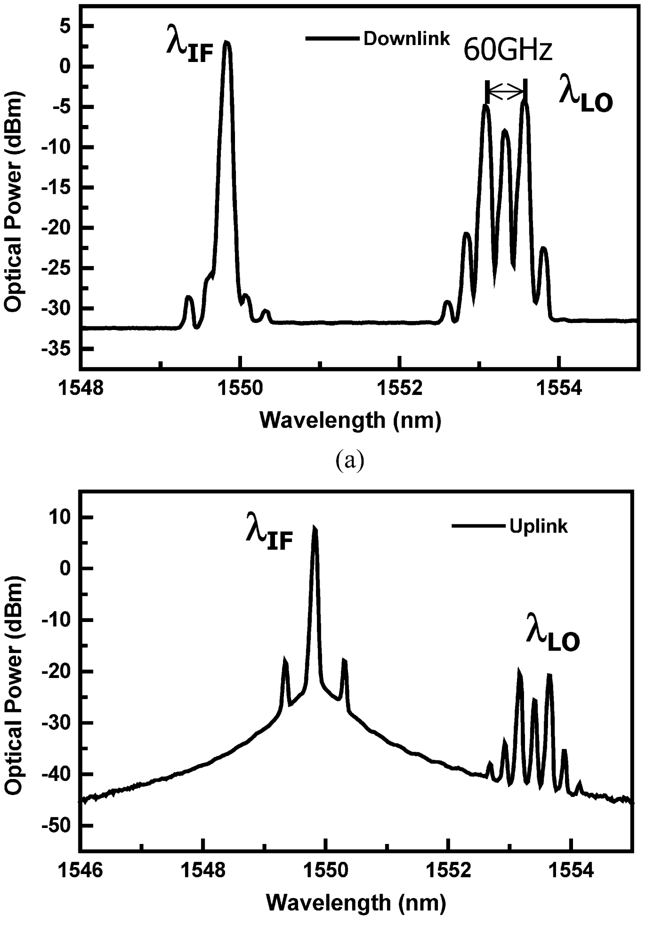
At first, the dependence of conversion efficiency on EAM bias was measured. The power of optical IF signals and optical LO signals before the SOA were -8 and -15 dBm, respectively. As shown in Fig. 5, η_{up} increases with increasing EAM reverse bias voltages because photocurrents in the EAM increase at high reverse voltages [4], but η_{down} decreases with increasing EAM reverse bias voltages because EAM nonlinearity is more pronounced at low reverse voltages.

LO power influences the efficiency of frequency converters. We investigated the dependence of frequency-conversion efficiencies on the SOA input optical LO power. For this measurement, optical IF power was set at -8 dBm, and the EAM was biased at -2.5 V. The results were obtained at two different SOA current levels in order to determine the influence of SOA gain on conversion efficiencies. As can be seen in Fig. 6(a) and (b), both η_{up} and η_{down} increase with optical LO power. For η_{up}, the increase is due to square-law beating power increase with an optical LO in the EAM. η_{down} increases because the photogenerated LO signal power in the EAM increases with optical LO power. In both cases, conversion efficiencies improve approximately 10 dB with an increase in the SOA bias from 100 to 150 mA, which corresponds to approximately a 5-dB increase in the SOA optical gain.

Fig. 6 shows that the down-conversion efficiency is much smaller than the up-conversion efficiency. The main reason for this is that the EAM device used in the experiment is optimized for linear optical modulation, not for nonlinear characteristics required for down-conversion. Improvement in down-conversion efficiencies are expected with changes in EAM device structure.

IV. BI-DIRECTIONAL 60-GHz RoF SYSTEM DEMONSTRATION

Fig. 7 shows the experimental setup for 60-GHz-band RoF systems using the SOA–EAM frequency converter. 60-GHz optical heterodyne LO signals at 1553.3 nm were generated by modulation of a Mach–Zehnder modulator biased at the minimum transmission point with 30-GHz signals. For downlink, optical IF signals at 1550 nm were produced by modulation of another Mach–Zehnder modulator with 10-Mb/s QPSK data at 100-MHz IF. Both optical signals were combined and injected into the cascaded SOA–EAM, producing frequency up-converted signals in the 60-GHz band. These two sidebands of frequency up-converted signals were frequency down-converted to 100 MHz by a subharmonic mixer with a 30-GHz electrical LO signal. The EVMs of recovered IF signals were analyzed by a vector signal analyzer (VSA). The SOA was biased at 150 mA, and the EAM was biased at -2.5 V. For the uplink data transmission, 10-Mb/s QPSK data signals at 59.85 GHz were generated by up-converting 150-MHz IF data to 59.85 GHz. The RF bandpass filter was used to suppress both LO carrier and image signals. When the EAM was modulated by uplink RF signals, frequency down-converted signals at 150 MHz were produced by the SOA–EAM frequency down-converter, which then modulated optical IF signals returning to the central station. In the central station, optical IF signals were photodetected after optical amplification and filtering, and the resulting QPSK data at 150 MHz were analyzed for transmission quality by VSA. All the experiments were done in a back-to-back condition with separate uplink and downlink data transmission. It should be noted that 60-GHz band should provide much higher bandwidth than the data bandwidth used in our demonstration. The bandwidth in our experiment was limited by data generation and analysis instruments available to us, not by the SOA–EAM frequency converter. Our frequency converter should have as wide a conversion bandwidth as its optical modulation and photodetection bandwidth. The EAM used in the experiment has 2-GHz modulation bandwidth at 60 GHz, and SOA cross-gain modulation bandwidth should be in the gigahertz range, as reported in [14]. Fig. 8(a) and (b) shows the optical spectra of downlink and uplink signals, respectively. The downlink optical spectrum shown in Fig. 8(a) was obtained from the optical signals coming out of the SOA (measured at Point A in Fig. 7), and a 1550-nm optical IF (λ_{IF}) and 1553.3-nm optical LO (λ_{LO}) signals can be seen. The additional peaks observed around λ_{LO} are due to modulation



(a)

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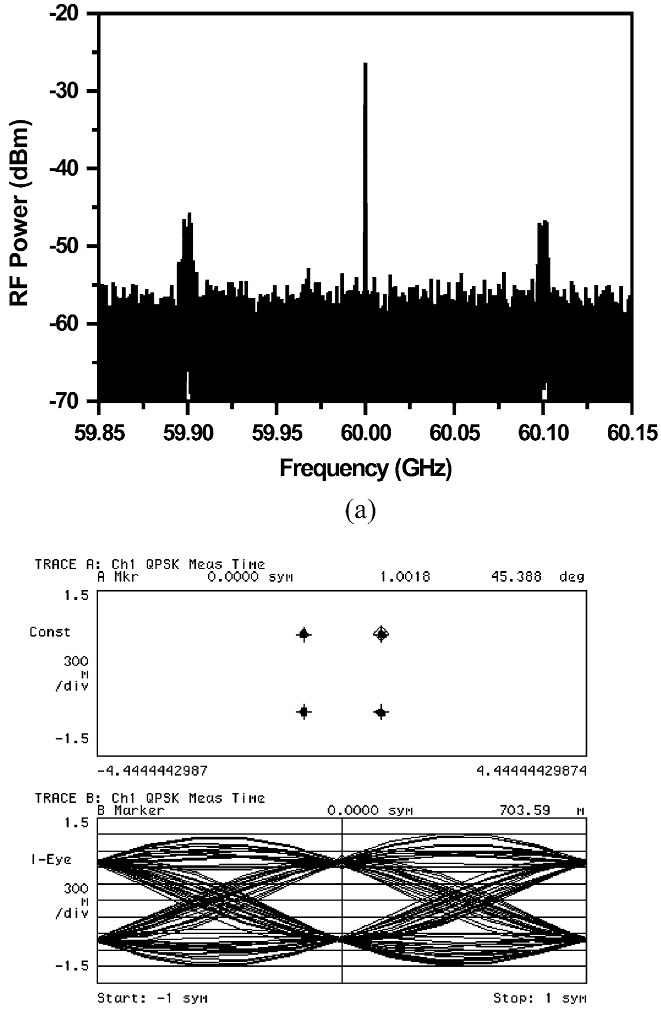
Fig. 8. Optical spectra of: (a) downlink signals and (b) uplink signals.



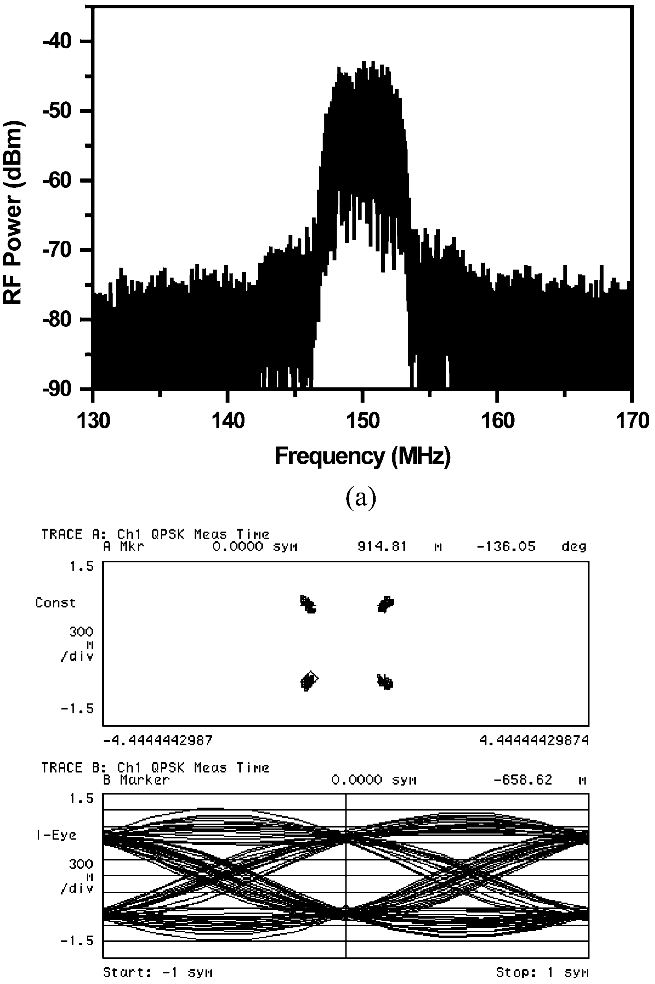
(a)

(b)

Fig. 9. (a) RF spectrum of frequency up-converted downlink signals. (b) Constellation and eye diagram of the demodulated downlink QPSK data signal.

harmonics of the Mach–Zehnder modulator [21]. The small peaks around λ_{IF} are due to cross-gain modulation between optical LO and IF signals. The uplink optical spectrum was measured after the optical bandpass filter ($\lambda_{\mathrm{pass}} = 1550$ nm) at the central station (measured at Point B in Fig. 7). As shown in Fig. 8(b), the optical LO signals are suppressed approximately 30 dB compared with optical IF signals. The side peaks around λ_{IF} are the results of f_{RF} modulation of the EAM.

The RF spectra and EVMs of frequency-converted QPSK data signals were measured. Fig. 9(a) shows the RF spectrum of frequency up-converted downlink signals, and Fig. 9(b) shows the constellation and eye diagram of demodulated downlink data. For this measurement, a -16.3-dBm optical LO and -10-dBm optical IF signals were injected into the SOA, and the resulting EVM was approximately 3.3%, which corresponds to 29.6-dB SNR. Fig. 10(a) shows the 150-MHz RF spectrum of frequency down-converted uplink signals measured at the central station, and Fig. 10(b) shows the constellation and eye diagram of demodulated uplink data. With -15-dBm optical LO and -8-dBm optical IF signals injected into the SOA, the EVM of 7.4% was obtained, which corresponds to 22.6-dB SNR.



(a)

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Fig. 10. (a) RF spectrum of the frequency down-converted uplink signals. (b) Constellation and eye diagram of the demodulated uplink QPSK data signal.

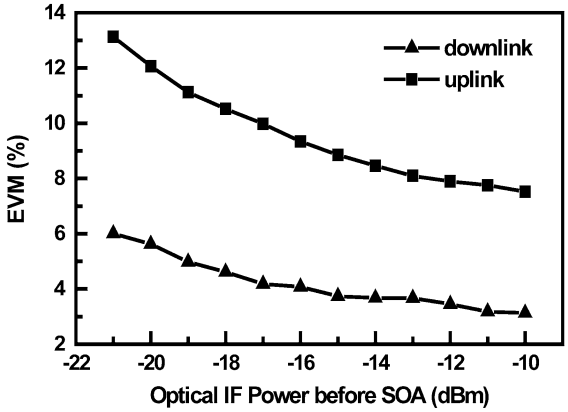


Fig. 11. Measured EVMs as a function of SOA input optical IF signal power for downlink and uplink.

We also measured EVMs as a function of optical IF power before the SOA for both downlink and uplink. Fig. 11 shows the measurement results. The optical LO power was fixed at -16.3 dBm for downlink and -15 dBm for uplink. As shown in this figure, downlink EVM changes from 6% to 3% as optical IF power increases. This is simply because lower optical

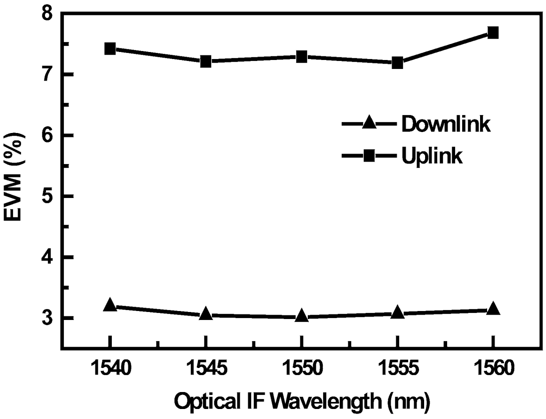


Fig. 12. Measured EVMs as a function of optical IF signal wavelength for downlink and uplink.

IF power reduces cross-gain modulation efficiency and the frequency up-converted signal power. However, when optical IF power is high, both cross-gain modulation efficiency and SOA gain of optical LO signals are saturated and, consequently, the EVM is also saturated at around 3%.

The EVM of the uplink data transmission also decreases from 13% to 8% as optical IF power increases. In uplink, the increase in optical IF power leads to increase in the detected uplink signal power, causing an increase in the SNR. Consequently, the EVM decreases until it is saturated due to SOA gain saturation. Although large EVMs were measured at low optical IF power conditions, their values are still good enough for QPSK data transmission.

The dependence of EVM on an optical IF wavelength was also investigated in order to identify the usable IF wavelength range. The optical LO power was −16.3 dBm for downlink and −15 dBm for uplink, and optical IF power was −10 dBm for downlink and −8 dBm for uplink. As shown in Fig. 12, EVMs for both downlink and uplink do not change very much with optical IF wavelength. This verifies that optical IF signals having different wavelengths can be used for accessing different base stations, as shown in Fig. 1.

V. CONCLUSION

We experimentally investigated and demonstrated the cascaded SOA–EAM millimeter-wave frequency up/down converter for bi-directional RoF systems. This configuration uses SOA cross-gain modulation and EAM photodetection for frequency up-conversion, and EAM nonlinearity for frequency down-conversion. With this single configuration and remotely fed optical LO and IF signals, both frequency up- and down-conversion are possible, which makes the base station very simple and RoF systems very flexible. We found that EAM biases affect frequency up- and down-conversion efficiencies. It was also found that high optical LO power provides high conversion efficiencies. We experimentally demonstrated 60-GHz bi-directional RoF systems using the SOA–EAM frequency converter. 10-Mb/s QPSK data at 100-MHz IF were optically transmitted to the base station and frequency up-converted to 60-GHz band. For uplink, 10-Mb/s QPSK data at 150-MHz IF were frequency down-converted from 60-GHz band and, after optical IF modulation, transmitted to the central station. The measured EVMs confirmed high-quality data transmission for both links for a wide range of optical IF wavelengths. We believe that this frequency converter is very useful for simplifying base stations and achieving flexible bi-directional RoF systems.

REFERENCES

[1] J. Mikkonen, C. Corrado, C. Evci, and M. Prögler, "Emerging wireless broad-band networks," *IEEE Commun. Mag.*, pp. 112–117, Feb. 1998.

[2] P. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: Prospects and future directions," *IEEE Commun. Mag.*, pp. 140–147, Jan. 2002.

[3] H. Ogawa, D. Polifko, and S. Banda, "Millimeter-wave fiber optics systems for personal radio communication," *IEEE Trans. Microw Theory Tech.*, vol. 40, no. 12, pp. 2285–2293, Dec. 1992.

[4] L. Noël, D. Wake, D. G. Moodie, D. D. Marcenac, L. D. Westbrook, and D. Nesset, "Novel technique for high-capacity 60 GHz fiber-radio transmission systems," *IEEE Trans. Microw Theory Tech.*, vol. 45, no. 8, pp. 1416–1423, Aug. 1997.

[5] A. J. Seeds, "Microwave photonics," *IEEE Trans. Microw Theory Tech.*, vol. 50, no. 3, pp. 877–887, Mar. 2002.

[6] U. Gliese, S. Nørskov, and T. N. Nielsen, "Chromatic dispersion in fiber-optic microwave and millimeter-wave links," *IEEE Trans. Microw Theory Tech.*, vol. 44, no. 10, pp. 1716–1724, Oct. 1996.

[7] H. Sotobayashi and K. Kitayama, "Cancellation of the signal fading for 60 GHz subcarrier multiplexed optical DSB signal transmission in nondispersion shifted fiber using midway optical phase conjugation," *J. Lightw. Technol.*, vol. 17, no. 12, pp. 2488–2497, Dec. 1999.

[8] F. Ramos, J. Marti, and V. Polo, "Compensation of chromatic dispersion effects in microwave/millimeter-wave optical systems using four-wave-mixing induced in dispersion-shifted fibers," *IEEE Photon. Technol. Lett.*, vol. 11, no. 9, pp. 1171–1173, Sep. 1999.

[9] E. Suematsu and N. Imai, "A fiber-optic/millimeter-wave radio transmission link using HBT as direct photodetector and an optoelectronic upconverter," *IEEE Trans. Microw Theory Tech.*, vol. 44, no. 1, pp. 133–143, Jan. 1996.

[10] G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Trans. Microw Theory Tech.*, vol. 45, no. 8, pp. 1410–1415, Aug. 1997.

[11] M. Tsuchiya and T. Hoshida, "Nonlinear photodetection scheme and its system applications to fiber-optic millimeter-wave wireless down-links," *IEEE Trans. Microw Theory Tech.*, vol. 47, no. 7, pp. 1342–1350, Jul. 1999.

[12] M. Ogusu, K. Inagaki, Y. Mizuguchi, and T. Ohira, "Carrier generation and data transmission on millimeter-wave bands using two-mode locked Fabry–Perot slave lasers," *IEEE Trans. Microw Theory Tech.*, vol. 51, no. 2, pp. 382–391, Feb. 2003.

[13] T. Kuri, K. Kitayama, and Y. Ogawa, "Fiber-optic millimeter-wave uplink system incorporating remotely fed 60-GHz-band optical pilot tone," *IEEE Trans. Microw Theory Tech.*, vol. 47, no. 7, pp. 1332–1337, Jul. 1999.

[14] Y.-K. Seo, J.-H. Seo, and W.-Y. Choi, "Photonic frequency upconversion efficiencies in semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 5, pp. 751–753, May 2003.

[15] J.-H. Seo, Y.-K. Seo, and W.-Y. Choi, "Spurious-free dynamic range characteristics of the photonic up-converter based on a semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 11, pp. 1591–1593, Nov. 2003.

[16] J. Lim, Y.-S. Kang, K.-S. Choi, J.-H. Lee, S.-B. Kim, and J. Kim, "Analysis and characterization of traveling-wave electrode in electroabsorption modulator for radio-on-fiber application," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3004–3010, Dec. 2003.

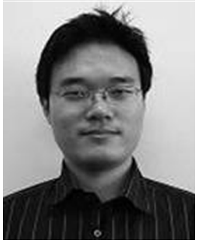
[17] K. Kitayama, A. Stöhr, T. Kuri, R. Heinzelmann, D. Jäger, and Y. Takahashi, "An approach to single optical component antenna base stations for broad-band millimeter-wave fiber-radio access systems," *Trans. Microw Theory Tech.*, vol. 48, no. 12, pp. 2588–2595, Dec. 2000.

[18] J.-H. Seo, C.-S. Choi, W.-Y. Choi, Y.-S. Kang, Y.-D. Chung, and J. Kim, "Remote optoelectronic frequency down-conversion using 60 GHz optical heterodyne signals and electroabsorption modulator," *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 1073–1075, May 2005.

[19] K. Asaka, Y. Suzaki, Y. Kawaguchi, S. Kondo, Y. Noguchi, H. Okamoto, R. Iga, and S. Oku, “Lossless electroabsorption modulator monolithically integrated with a semiconductor optical amplifier and a passive waveguide,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 5, pp. 679–681, May 2003.

[20] D. M. Pozar, *Microwave and RF Design of Wireless Systems*. New York: Wiley, 2001.

[21] J. O’Reilly and P. Lane, “Remote delivery of video services using mm-waves and optics,” *J. Lightw. Technol.*, vol. 12, no. 2, pp. 369–375, Feb. 1994.



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