Self-Oscillating Harmonic Opto-Electronic Mixer Based on a CMOS-Compatible Avalanche Photodetector for Fiber-Fed 60-GHz Self-Heterodyne Systems

Myung-Jae Lee, *Student Member, IEEE*, Hyo-Soon Kang, *Student Member, IEEE*,
Kwang-Hyun Lee, and Woo-Young Choi, *Member, IEEE*

***Abstract*—A self-oscillating harmonic opto-electronic mixer based on a CMOS-compatible avalanche photodetector for fiber-fed 60-GHz self-heterodyne systems is demonstrated. The mixer is composed of an avalanche photodetector fabricated with 0.18-μm standard CMOS process and an electrical feedback loop for self oscillation. It simultaneously performs photodetection and frequency up-conversion of photodetected signals into the second harmonic self-oscillation frequency band. The avalanche photodetector and the mixer are characterized and analyzed, and the RF avalanche multiplication factor is investigated. In addition, conversion efficiency as well as internal conversion gain is determined, and bias conditions are optimized for the best self-oscillating harmonic opto-electronic mixer performance. Data transmission of 5-MS/s 32 quadrature amplitude modulation signals using self-oscillating harmonic opto-electronic mixer is successfully demonstrated.**

***Index Terms*—Avalanche photodetector, CMOS-compatible photodetector, fiber-fed system, opto-electronic mixer, self-heterodyne system, self-oscillating mixer, 60-GHz band.**

I. INTRODUCTION

MILLIMETER-WAVE systems have been extensively investigated for broadband wireless communications. In particular, 60-GHz wireless systems have been pursued due to the availability of about 7 GHz of license-free band around 60 GHz. The small wavelength of 60-GHz signals makes possible small RF components and antennas. For these reasons, HDTV wireless transmissions [1], [2], high-speed wireless local area networks (WLANs) [3], and high-speed wireless personal area networks (WPANs) [4] have been considered as applications of 60-GHz wireless systems. However, there still is a difficulty in realizing low-cost millimeter-wave components [5]. Using self-heterodyne systems, the cost of millimeter-wave wireless systems can be reduced. In self-heterodyne systems, RF data signals are transmitted simultaneously with local oscillator (LO) signals and received RF signals are frequency down-converted with the transmitted LO signals in a square-law detector at a mobile terminal [6]. Consequently, a millimeter-wave LO is not needed in the mobile terminal, resulting in cost reduction.

With development of fiber-optic technologies, fiber-fed millimeter-wave wireless systems have become a promising technology for next-generation broadband communication systems due to such advantages of optical fiber as low loss, large bandwidth, and highly flexible transmission medium [7]–[9]. In these systems, broadband data signals are optically distributed from a central office to antenna base stations via optical fiber and then transmitted to mobile terminals through wireless links. Because the free-space propagation loss in millimeter waves is very high, numerous antenna base stations are required. Therefore, cost-effective antenna base stations are very important for realizing fiber-fed 60-GHz wireless systems.

There are several methods for realizing low-cost antenna base stations. Phototransistors based on InP high electron-mobility transistors (HEMTs) [8] and InP-InGaAs heterojunction phototransistors (HPTs) [10] can be used as an opto-electronic mixer for antenna base stations. However, InP and InP–InGaAs based components are not very cost effective yet. An opto-electronic mixer based on a CMOS-compatible avalanche photodetector [11] is an attractive solution because, as well known, CMOS technology can provide a high integration level at low costs.

We have previously proposed a fiber-fed 60-GHz self-heterodyne system based on a CMOS-compatible harmonic opto-electronic mixer, and demonstrated data transmission [12]. This system can be a solution for low-cost fiber-fed millimeter-wave wireless systems because low-cost antenna base stations and mobile terminals are possible. However, an additional LO was needed for frequency up-conversion in an antenna base station. In this work, we propose a self-oscillating harmonic opto-electronic mixer that can be used in fiber-fed 60-GHz self-heterodyne systems. A CMOS-compatible avalanche photodetector is used in the mixer. The avalanche photodetector performs photodetection as well as

---

Manuscript received April 15, 2008; revised August 19, 2008. First published November 18, 2008; current version published December 05, 2008. This work was supported by the Ministry of Information and Communication (MIC), Korea, under the Information Technology Research Center (ITRC) support program supervised by the Institute of Information Technology Advancement (IITA).

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

K.-H. Lee was with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea. He is now with the Samsung Electronics Company Ltd., Hwasung-si, Kyunggi-do 445-701, Korea (e-mail: optics@yonsei.ac.kr).

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

Digital Object Identifier 10.1109/TMTT.2008.2007141

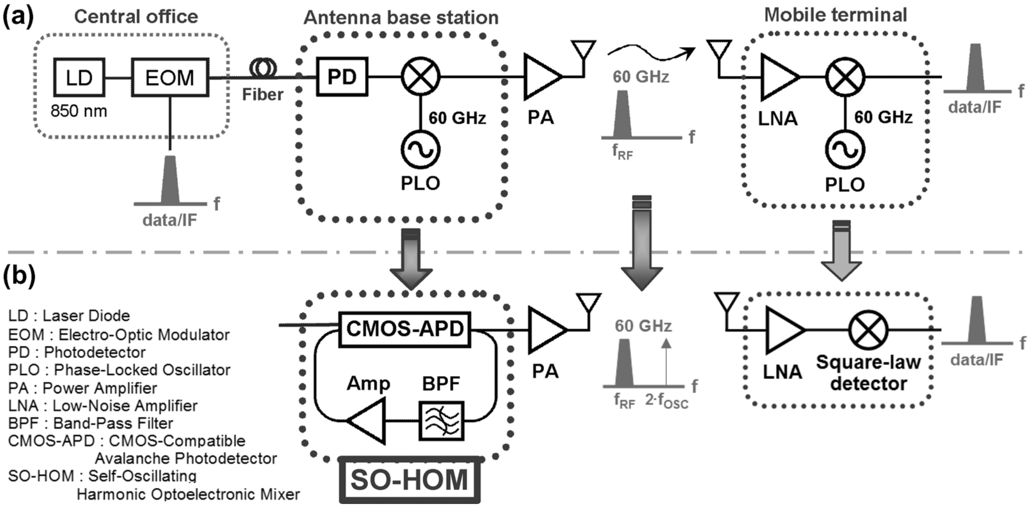


Fig. 1. (a) Configuration of a conventional fiber-fed 60-GHz system. (b) Configuration of a fiber-fed 60-GHz self-heterodyne system based on the self-oscillating harmonic opto-electronic mixer. From [13].

harmonic frequency up-conversion, and an electrical feedback loop having a bandpass filter and an amplifier generates LO signals by self oscillation. Initial results of our investigation have been presented in [13]. In this paper, we explain the structure and characteristics of the CMOS-compatible avalanche photodetector in detail. In addition, the characteristics of the self-oscillating harmonic opto-electronic mixer are analyzed, and the RF avalanche multiplication factor is measured and modeled. To evaluate the performance of the mixer, fundamental and harmonic frequency up-converted signal powers are measured and analyzed using the nonlinear coefficients obtained from the RF avalanche multiplication factor. The conversion efficiency as well as internal conversion gain is determined, and bias conditions are characterized and optimized.

This paper is organized as follows. In Section II, the system architecture under investigation is explained. Section III describes operation principles and characteristics of the CMOS-compatible avalanche photodetector and self-oscillating harmonic opto-electronic mixer. Section IV presents results of our demonstration of 5-MS/s 32 quadrature amplitude modulation (QAM) data transmission in a fiber-fed 60-GHz self-heterodyne system based on the mixer.

II. Proposed Fiber-Fed 60-GHz Self-Heterodyne System Based on the Self-Oscillating Harmonic Opto-Electronic Mixer

Fig. 1(a) schematically shows a typical fiber-fed 60-GHz system [7]. In this system, optical IF signals are transmitted from the central office to the antenna base station through optical fiber. Transmitted IF signals are frequency up-converted to the 60-GHz band using a LO at the antenna base station and frequency up-converted signals are radiated to mobile terminals where received signals are frequency down-converted to IF band with a LO. This system requires two independent LOs operating at 60-GHz band for frequency up/down-conversion. Moreover, LOs should generate stable and low phase-noise signals since their phase noises induce phase errors in transmitted and received data. However, it is still difficult to realize phase-locked oscillators at 60-GHz band in a cost-effective manner.

Fig. 1(b) shows the schematic diagram of our fiber-fed 60-GHz self-heterodyne system based on the self-oscillating harmonic opto-electronic mixer. As shown in the figure, optical signals modulated by electrical IF signals in the central office are transmitted to the antenna base station through optical fiber and injected to the mixer oscillating at f_{OSC}. Injected optical IF signals are photodetected by a CMOS-compatible avalanche photodetector in the mixer and frequency up-converted to the 60-GHz band, which corresponds to the second harmonic of f_{OSC}. This harmonic frequency up-conversion is due to the nonlinearity of avalanche multiplication process in the avalanche photodetector [11], and the high nonlinearity of avalanche multiplication process provides the possibility of achieving efficient harmonic opto-electronic mixing [14]. The self-oscillating harmonic opto-electronic mixer simultaneously performs photodetection and opto-electronic mixing without any LO. Frequency up-converted RF and LO signals produced by the mixer are radiated from the antenna base station to mobile terminals. Then, received RF and LO signals are self-mixed by a square-law detector, resulting in frequency down-converted IF signals in mobile terminals. In this system, LO phase quality is poor due to free-running oscillation in the self-oscillating harmonic opto-electronic mixer. However, this has no effect on the frequency down-converted IF signals since frequency down-conversion is performed by self-mixing between phase-correlated RF and LO signals [6]. Therefore, there is no need for the mobile terminal to include a phase-locked oscillator.

III. Self-Oscillating Harmonic Opto-Electronic Mixer Using the CMOS-Compatible Avalanche Photodetector

Fig. 2 describes the architecture of the self-oscillating harmonic opto-electronic mixer. In the mixer, the CMOS-compatible avalanche photodetector performs photodetection, as well as frequency up-conversion, and an electrical feedback

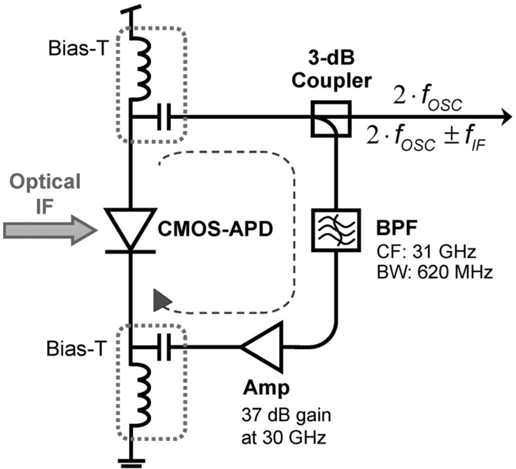


Fig. 2. Schematic diagram of the self-oscillating harmonic opto-electronic mixer based on the CMOS-compatible avalanche photodetector. From [13].

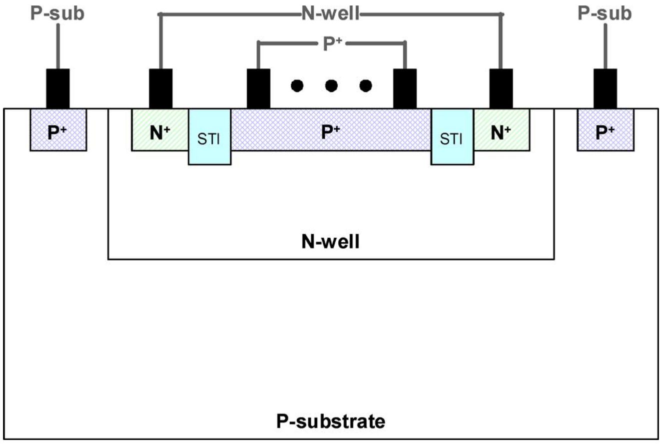


Fig. 3. Cross section of the fabricated CMOS-compatible avalanche photodetector. From [15].

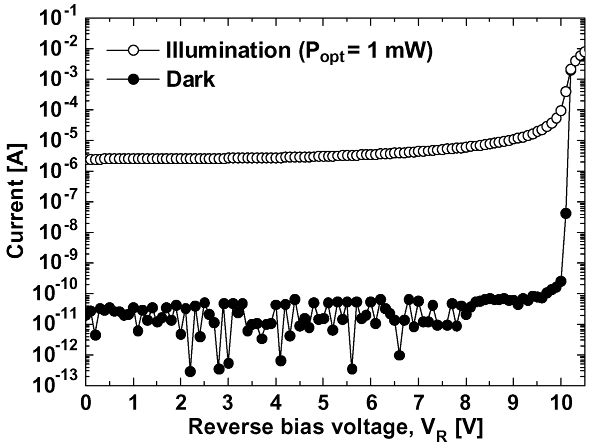


Fig. 4. Current–voltage characteristics of the fabricated CMOS-compatible avalanche photodetector under dark and illumination conditions.

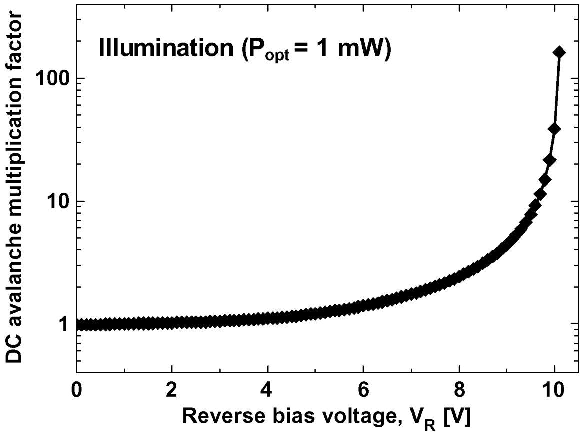


Fig. 5. DC avalanche multiplication factor as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector.

loop having a bandpass filter and an amplifier generates self-oscillation signals.

A. *CMOS-Compatible Avalanche Photodetector*

A CMOS-compatible avalanche photodetector was fabricated using 0.18-μm standard CMOS process and its structure is shown in Fig. 3 [15]. It is implemented using the vertical P-N junction formed by P^+ source/drain to N-well region. Multifinger electrodes with 0.5 μm spacing are employed on the active area for the exclusion of the lateral diffusion path. The active area of the avalanche photodetector is about 30×30 μm^2 and the optical window is formed by blocking the salicide during the fabrication.

Fig. 4 shows current–voltage characteristics of the fabricated CMOS-compatible avalanche photodetector under dark and illumination conditions. The incident optical power is 1 mW. The avalanche breakdown voltage is about 10.25 V and the maximum responsivity is about 0.417 A/W. Fig. 5 shows the dc avalanche multiplication factor as a function of the applied reverse bias voltage. The dc avalanche multiplication factor can be determined as

$$M_{\mathrm{DC}}(V) = \frac{I_{\mathrm{illum}}(V) - I_{\mathrm{dark}}(V)}{I_{\mathrm{illum}}(V_0) - I_{\mathrm{dark}}(V_0)} \qquad (1)$$

where I_{illum} is the current under illumination, I_{dark} is the current under dark, and V_0 is the reference voltage at which avalanche multiplication is insignificant. In Fig. 5, $V_0 = 1$ V is used. The maximum value of the dc avalanche multiplication factor is about 162 at $V_R = 10.1$ V.

B. *Self-Oscillating Harmonic Opto-Electronic Mixer*

An oscillator is formed by applying an electrical feedback loop, which consists of a bandpass filter and an amplifier. For self oscillation without any optical injection, the CMOS-compatible avalanche photodetector acts as a capacitor. The mixer output signals are extracted using a 3-dB coupler. The self-oscillation frequency is determined by the bandpass filter bandwidth. Although discrete components are used for our present investigation, a single-chip approach based on CMOS technology is possible, which can provide further cost reduction and simplification of antenna base stations.

Fig. 6 shows the spectrum of the second harmonic of self-oscillation frequency of the self- oscillating harmonic opto-electronic mixer. Although this self-oscillation signal is very sensitive to environmental conditions, this does not matter in self- heterodyne systems as mentioned above. When optical IF signals are injected to the CMOS-compatible avalanche

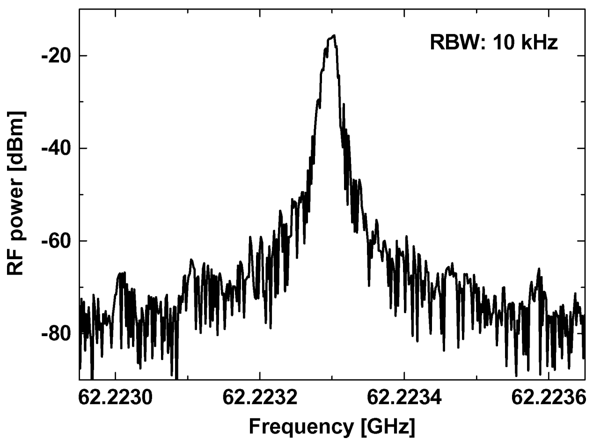


Fig. 6. Measured spectrum of the second harmonic of self-oscillation frequency of the self-oscillating harmonic opto-electronic mixer.

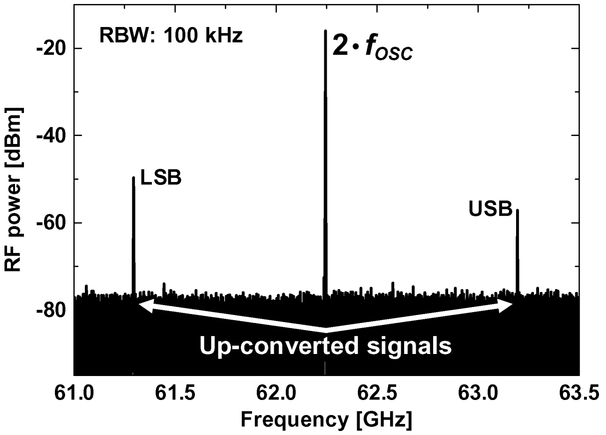


Fig. 7. Measured spectrum of frequency up-converted signals and second harmonic of self-oscillation frequency of the self-oscillating harmonic opto-electronic mixer. LSB: lower sideband, USB: upper sideband. From [13].

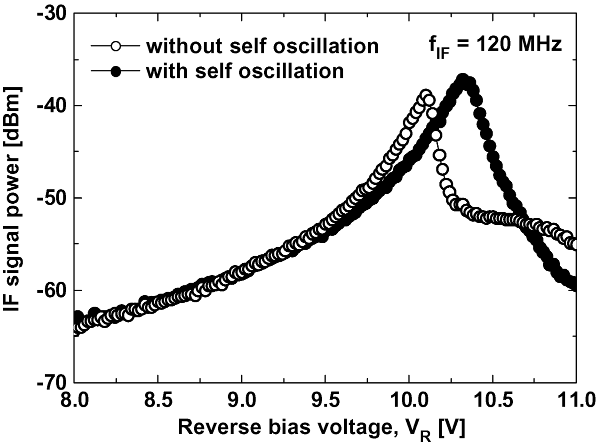


Fig. 8. IF signal powers as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector at the output of the self-oscillating harmonic opto-electronic mixer.

photodetector, the mixer generates frequency up-converted signals using the self-oscillation signals. Fig. 7 shows the resulting frequency up-converted signals when 1 dBm 950 MHz (f_{IF}) optical signals are injected to the avalanche photodetector biased at the reverse bias voltage of 10.3 V. The spectrum clearly shows double sideband signals at $2 \cdot f_{\mathrm{OSC}} \pm f_{\mathrm{IF}}$. As state above, this frequency up-conversion is due to the nonlinearity of avalanche multiplication process in the avalanche photodetector.

The operation of the self-oscillating harmonic opto-electronic mixer can be analyzed as follows. When optical signals are illuminated to a CMOS-compatible avalanche photodetector, the generated photocurrent can be expressed as

$$I_{ph} = R_0 \cdot P_{\mathrm{opt}} \cdot M_{\mathrm{RF}}(v) \tag{2}$$

where R_0 is the intrinsic responsivity of the CMOS-compatible avalanche photodetector at unit gain, P_{opt} is the incident optical power, $M_{\mathrm{RF}}(v)$ is the RF avalanche multiplication factor, and v is the instantaneous reverse bias voltage. The IF modulated optical signal power is described as

$$P_{\mathrm{opt}} = P_0\left[1 + m\cos(2\pi f_{\mathrm{IF}} t)\right] \tag{3}$$

where P_0 is the average optical power, m is the optical modulation index, and f_{IF} is the frequency of IF signal. The reverse bias voltage is modulated by the self-oscillation signal, resulting in

$$v = V_R + V_{\mathrm{OSC}}\cos(2\pi f_{\mathrm{OSC}} t) \tag{4}$$

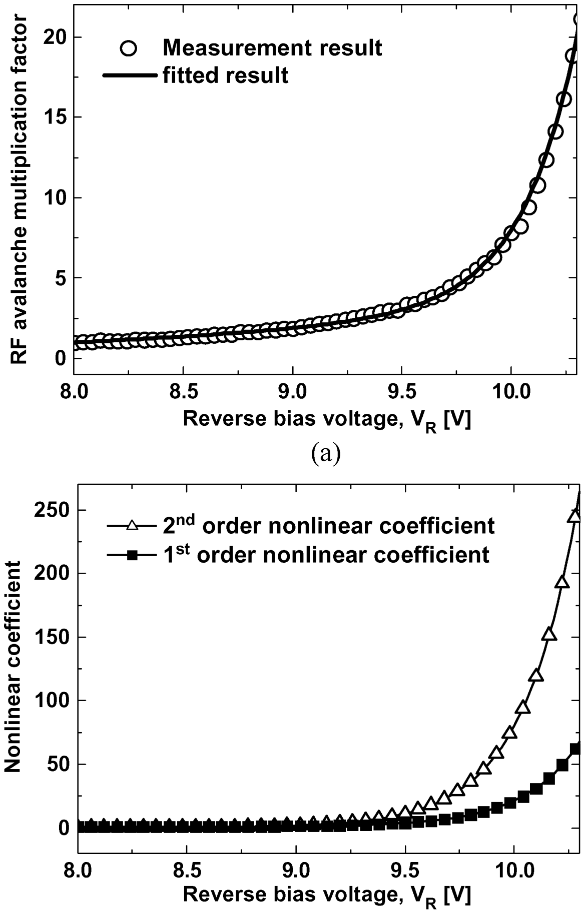
where V_R is the reverse bias voltage, V_{OSC} is the peak voltage of the self-oscillation signal, and f_{OSC} is the self-oscillation frequency.

The RF avalanche multiplication factor can be determined by combining (2) and (3) as

$$M_{\mathrm{RF}}(v) = \frac{I_{ph}}{R_0 \cdot P_0 \cdot m}. \tag{5}$$

In actual measurement, this RF avalanche multiplication factor produces different values from the dc case as the spectrum analyzer used for RF measurement has 50-Ω termination whereas the dc current meter does not. For our analysis, the RF avalanche multiplication factor measured with the spectrum analyzer is used.

Fig. 8 shows optical IF signals detected at the self-oscillating harmonic opto-electronic mixer output as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector with and without the injection of the self-oscillation signal. The maximum photodetected IF signal power is obtained at the reverse bias voltage of 10.1 V owing to maximized avalanche multiplication factor without self oscillation. With self oscillation, however, the maximum point is shifted to the higher reverse bias voltage. This is because of the generated dc components. When the self-oscillation signal is injected



(a)

(b)

Fig. 9. (a) RF avalanche multiplication factor and (b) its nonlinear coefficients as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector.

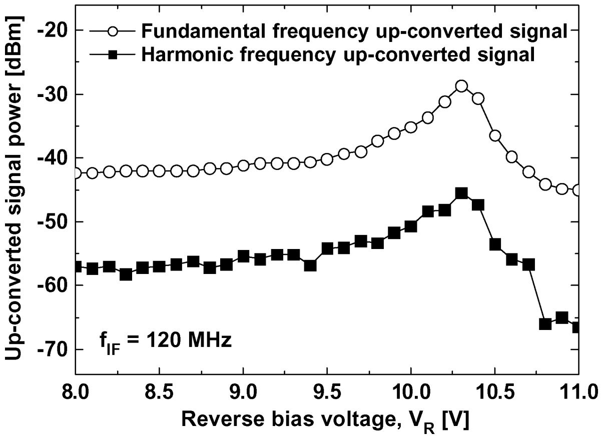


Fig. 10. Fundamental and harmonic frequency up-converted signal powers as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector.

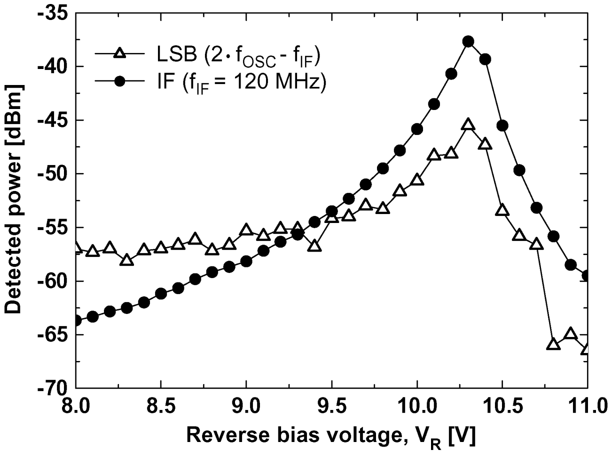


Fig. 11. Frequency up-converted signal and IF signal powers as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector. LSB: lower sideband.

to the avalanche photodetector, dc components as well as harmonic components are generated at the output due to the nonlinearity of the avalanche photodetector. In order to achieve the maximum IF signal power, therefore, the bias voltage of the avalanche photodetector should be changed to the reverse bias voltage of 10.3 V in self-oscillation conditions.

Fig. 9(a) shows the measured RF avalanche multiplication factor as a function of the reverse bias voltage. Hollow circles represent the measurement results, and the solid line is the fitted result. The RF avalanche multiplication factor can be modeled by the empirical expression as follows:

$$M_{\mathrm{RF}}(v) = \left(\frac{v}{8}\right)^5 + \exp\left(4(v - 9.6)\right), \qquad 8 \le V_R \le 10.3 \tag{6}$$

Fig. 9(b) represents the first-order nonlinear coefficient (a_1) and second-order nonlinear coefficient (a_2) of the RF avalanche multiplication factor, which can be obtained by 1st derivative and second derivative of $M_{\mathrm{RF}}(v)$, respectively.

To evaluate the performance of the self-oscillating harmonic opto-electronic mixer, fundamental (30-GHz band) and harmonic (60-GHz band) frequency up-converted signal powers were measured at the lower sideband, and the results are shown in Fig. 10. The opto-electronic mixing products can be considered as

$$\text{Fundamental} \propto (a_1 V_{\mathrm{OSC}})^2 \tag{7}$$

$$\text{Harmonic} \propto \left(a_2 V_{\mathrm{OSC}}^2\right)^2. \tag{8}$$

Although the second-order nonlinear coefficient is larger than the first-order nonlinear coefficient as shown in Fig. 9(b), the harmonic frequency up-converted signal power is about 15 dB lower than the fundamental frequency up-converted signal power due to the small V_{OSC}, as can be seen in (7) and (8).

Fig. 11 shows the dependence of the harmonic frequency up-converted signal and IF signal powers on the reverse bias voltage of the CMOS-compatible avalanche photodetector. The frequency up-converted signal power increases as the reverse bias voltage increases up to 10.3 V. It has maximum value at 10.3 V because RF avalanche multiplication factor is maximized at this voltage. The maximum value shows an increase, as compared with the result using external LO due to the self-oscillating structure [11].

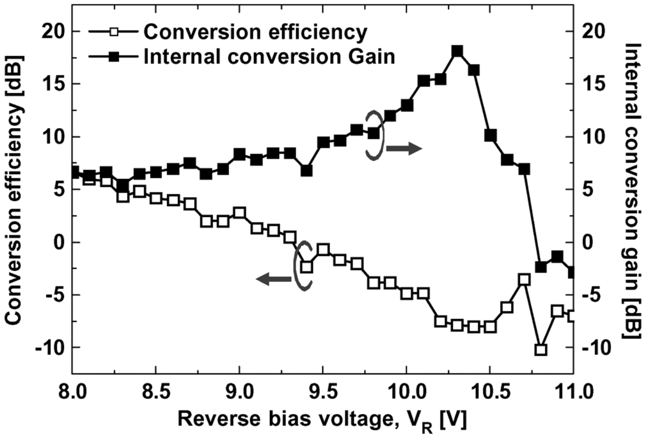


Fig. 12. Conversion efficiency and internal conversion gain as a function of the reverse bias voltage of the CMOS-compatible avalanche photodetector.

Fig. 12 shows conversion efficiency for opto-electronic harmonic frequency up-conversion to 60 GHz. The conversion efficiency of the self-oscillating harmonic opto-electronic mixer is defined as the ratio of the frequency up-converted signal power to the input IF signal power [14]. On the other hand, the mixer provides internal gain with the help of avalanche multiplication process, thus internal conversion gain can be defined as the power ratio of the frequency up-converted signal to the primary photodetected signal without avalanche gain as in opto-electronic mixer based on phototransistors [8]. The primary photodetected signal power was determined about −63.7 dBm at V_R of 8 V in Fig. 11. Fig. 12 also shows the internal conversion gain, and the maximum internal conversion gain of about 18.2 dB at the reverse bias voltage of 10.3 V is obtained with the self-oscillating harmonic opto-electronic mixer.

IV. DEMONSTRATION OF FIBER-FED 60-GHz SELF-HETERODYNE SYSTEM BASED ON THE SELF-OSCILLATING HARMONIC OPTO-ELECTRONIC MIXER

Downlink data transmission of 5-MS/s 32 QAM data signals in the 60-GHz band was demonstrated. In the central office, 850-nm optical signals were modulated by electrical 950 MHz IF data signals using an electro-optic modulator. The generated optical IF data signals are transmitted to the antenna base station via 2-m long multimode fiber. The transmitted optical IF data signals were photodetected by a CMOS-compatible avalanche photodetector and frequency up-converted to the 60-GHz band by the second harmonic of f_{OSC} using the self-oscillating harmonic opto-electronic mixer at the antenna base station. The reverse bias voltage of 10.3 V was applied to the CMOS-compatible avalanche photodetector. A 20-dB gain power amplifier was used to compensate the free-space propagation loss in the 60-GHz band. The output signals of the antenna base station were radiated to mobile terminals via 1-m free space using an antenna having 24-dBi gain. The wireless link gain including antennas was about −20 dB. At the mobile terminal, received data and LO signals were amplified by a 36.5-dB gain low-noise amplifier (LNA), and then frequency down-converted to IF band by a square-law detector.

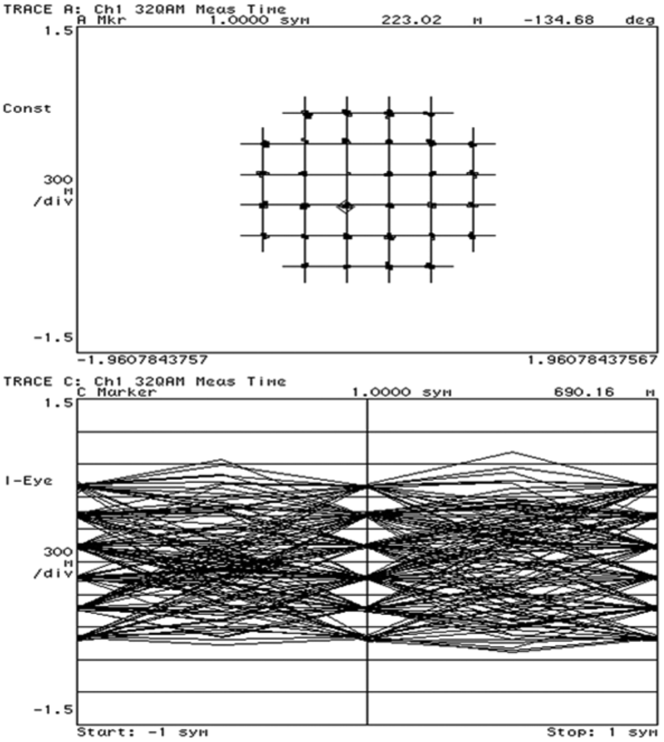


Fig. 13. Constellation and I-eye diagram of demodulated 5-MS/s 32 QAM data signals. From [13].

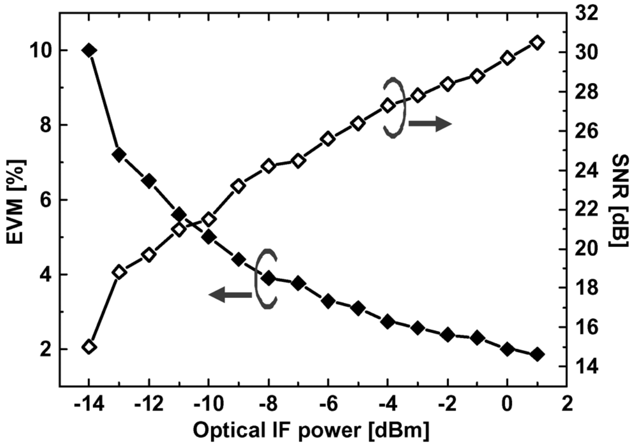


Fig. 14. EVM and SNR as a function of optical IF power. SNR: signal-to-noise ratio.

To evaluate the system performance, the frequency down-converted data signals were demodulated by a vector signal analyzer. Fig. 13 shows the constellation and the in-phase eye diagram of the demodulated 5 MS/s 32 QAM data signals. The eye was clearly open and the measured error vector magnitude (EVM) was about 1.83%, which corresponds to 30.7-dB signal-to-noise ratio. Compared with our previous work [12], the performance of the proposed system based on the self-oscillating harmonic opto-electronic mixer is significantly improved. The EVM is decreased by about 3.3%, and the signal-to-noise ratio is increased by about 9 dB. This EVM of the proposed system should be sufficient for many wireless applications. We measured EVM and signal-to-noise ratio as a function of optical IF power using an optical attenuator. As shown in Fig. 14, the EVM of the downlink data transmission deteriorates from 1.83% to 10%, and the signal-to-noise ratio diminishes from 30.7 dB to 15 dB as optical IF power decreases. The degradation of EVM and signal-to-noise ratio is simply due to the transmission loss in fiber. With a sufficiently high optical power source, the optical link distance between the central office and the antenna base station can reach a few hundred meters.

V. CONCLUSION

The self-oscillating harmonic opto-electronic mixer for fiber-fed 60-GHz self-heterodyne systems is proposed and characterized. Our mixer consists of a CMOS-compatible avalanche photodetector and the electric feedback loop including a bandpass filter and an amplifier. The mixer can provide photodetection, oscillation, and frequency mixing at the same time. Moreover, the need to supply a phase-locked oscillator is eliminated by using the self-heterodyne method. The proposed fiber-fed 60-GHz self-heterodyne system based on the mixer is especially fit for the millimeter-wave wireless systems where the number of antenna base stations and mobile terminals are large and the size of antenna base station is restricted. The CMOS-compatible avalanche photodetector and the self-oscillating harmonic opto-electronic mixer are characterized and analyzed, and the RF avalanche multiplication factor is measured and modeled. The performance of the mixer including up-converted signal power, conversion efficiency, and internal conversion gain is examined. Bias conditions are characterized and optimized for the best performance. Data transmission of 5 MS/s 32 QAM signals in a 60-GHz band is successfully performed with 1.83% EVM and 30.7-dB signal-to-noise ratio. Although the feedback loop was implemented by discrete components in our configuration, the entire self-oscillating harmonic opto-electronic mixer can be realized by a single-chip approach with integration of a CMOS-compatible avalanche photodetector and necessary high-speed CMOS circuits.

ACKNOWLEDGMENT

The authors acknowledge that the EDA software used in this work was supported by the IC Design Education Center (IDEC) of Korea.

REFERENCES

[1] Y. Katayama, C. Haymes, D. Nakano, T. Beukema, B. Floyd, S. Reynolds, U. Pfeiffer, B. Gaucher, and K. Schleupen, "2-Gbps uncompressed HDTV transmission over 60-GHz SiGe radio link," in *IEEE Consumer Commun. Networking Conf.*, Jan. 2007, pp. 12–16.

[2] B. Floyd, U. Pfeiffer, S. Reynolds, A. Valdes-Garcia, C. Haymes, Y. Katayama, D. Nakano, T. Beukema, B. Gaucher, and M. Soyuer, "Silicon millimeter-wave radio circuits at 60–100 GHz," in *IEEE Top. Silicon Monolithic Integr. Circuits RF Syst. Meeting*, Jan. 2007, pp. 213–218.

[3] G. Wu, Y. Hase, and M. Inoue, "An ATM-based indoor millimeter-wave wireless LAN for multimedia transmissions," *IEICE Trans. Commun.*, vol. E83-B, no. 8, pp. 1740–1752, Aug. 2000.

[4] *WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c)*, IEEE Standard 802.15, 2005. [Online]. Available: http://www.ieee802.org/15/pub/TG3c.html

[5] C. H. Doan, S. Emami, D. A. Sobel, A. M. Niknejad, and R. W. Brodersen, "Design considerations for 60 GHz CMOS radios," *IEEE Commun. Mag.*, vol. 42, pp. 132–140, Dec. 2004.

[6] Y. Shoji, K. Hamaguchi, and H. Ogawa, "Millimeter-wave remote self-heterodyne system for extremely stable and low-cost broad-band signal transmission," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 6, pp. 1458–1468, Jun. 2002.

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

[8] C.-S. Choi, H.-S. Kang, W.-Y. Choi, D.-H. Kim, and K.-S. Seo, "Phototransistors based on InP HEMTs and their applications to millimeter-wave radio-on-fiber systems," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 1, pp. 256–263, Jan. 2005.

[9] Y. L. Guennec, G. Maury, J. Yao, and B. Cabon, "New optical microwave up-conversion solution in radio-over-fiber networks for 60-GHz wireless applications," *J. Lightw. Technol.*, vol. 24, no. 3, pp. 1277–1282, Mar. 2006.

[10] C.-S. Choi, J.-H. Seo, W.-Y. Choi, H. Kamitsuna, M. Ida, and K. Kurishima, "60-GHz bidirectional radio-on-fiber links based on InP-InGaAs HPT optoelectronic mixers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2721–2723, Dec. 2005.

[11] H.-S. Kang and W.-Y. Choi, "CMOS-compatible 60 GHz harmonic optoelectronic mixer," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2007, pp. 233–236.

[12] H.-S. Kang and W.-Y. Choi, "Fibre-supported 60 GHz self-heterodyne systems based on CMOS-compatible harmonic optoelectronic mixers," *Electron. Lett.*, vol. 43, no. 20, pp. 1101–1103, Sep. 2007.

[13] M.-J. Lee, H.-S. Kang, K.-H. Lee, and W.-Y. Choi, "Fiber-fed 60-GHz self-heterodyne system using a self-oscillating harmonic optoelectronic mixer based on a CMOS-compatible APD," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2008, pp. 587–590.

[14] M. T. Abuelma'atti, "Theory of avalanche diode harmonic optoelectronic mixer," *Proc. Inst. Elect. Eng.*, vol. 135, pt. J, pp. 183–186, Apr. 1988.

[15] H.-S. Kang, M.-J. Lee, and W.-Y. Choi, "Si avalanche photodetectors fabricated in standard complementary metal–oxide–semiconductor process," *Appl. Phys. Lett.*, vol. 90, pp. 151118-1–151118-3, Apr. 2007.

Myung-Jae Lee (S'08) was born in Seoul, Korea, on July 4, 1981. He received the B.S. and M.S. degrees in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2006 and 2008, respectively, and is currently working toward the Ph.D. degree at Yonsei University. His master's thesis concerned the equivalent circuit model for CMOS-compatible avalanche photodetectors.

His research interests include CMOS-compatible photodetectors and receivers, millimeter-wave wireless systems, microwave photonics, and semiconductor devices.

Hyo-Soon Kang (S'05) was born in Seoul, Korea, in 1978. He received the B.S. and M.S. degrees in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2002 and 2004, respectively, and is currently working toward the Ph.D. degree at Yonsei University. His doctoral dissertation concerns CMOS-based Si opto-electronic devices and their applications to microwave/millimeter-wave photonics systems.

His other research interests include CMOS RF integrated circuits and millimeter-wave wireless systems.

Kwang-Hyun Lee received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2001, 2003, and 2008, respectively. His doctoral dissertation concerned opto-electronic oscillators and their applications to 60-GHz fiber-fed wireless systems.

In 2008, he joined the Samsung Eletronics Company Ltd., Hwasung-si, Kyunggi-do, Korea. His research interests include millimeter-wave wireless systems, high-speed opto-electronics, and microwave photonics.

Woo-Young Choi (M'92) received the B.S., M.S., and Ph.D. degrees in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT), Cambridge, in 1986, 1988, and 1994, respectively. His doctoral dissertation concerned the investigation of molecular-beam epitaxy (MBE)-grown InGaAlAs laser diodes for fiber-optic applications.

From 1994 to 1995, he was a Post-Doctoral Research Fellow with NTT Opto-Electronics Laboratories, where he studied femto-second all-optical switching devices based on low-temperature grown InGaAlAs quantum wells. In 1995, he joined the Department of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, where he is currently a Professor. His research interests are in the area of high-speed circuits and systems that include high-speed electronic circuits, high-speed opto-electronics, and microwave photonics.