Proceedings
2010 IEEE International Topical Meeting on microwave photonics

MWP 2010 MONTRÉAL

Technically supported by

IEEE photonics SOCIETY

MTT-S IEEE

IEEE Catalog Number: CFP10756-PRT
ISBN: 978-1-4244-7822-4

Session WE4: *Poster Session I – Microwave Photonics Devices and Systems*

16:00-17:30 *Fontaine GH*
Session Co-Chairs:
Arye Rosen, Drexel University, United States
Asher Madjar, M2 Microwaves LLC, United States

Session TH1: *Photonic Generation of Microwave and THz Signals*

8:00-10:00 *Verdun/Lachine/Lasalle Ballroom*
Session Co-Chairs:
Alwyn Seeds, University College London, United Kingdom
Idelfonso Tafur Monroy, DTU Fotonik, Denmark

60GHz CMOS-APD Optoelectronic Mixers with Optimized Conversion Efficiency

Jae-Young Kim, Myung-Jae Lee and Woo-Young Choi

Department of Electrical Electronic Engineering

Yonsei University

Seoul, Korea

wchoi@yonsei.ac.kr

***Abstract*—A harmonic optoelectronic mixer based on CMOS avalanche photodiode is designed for optimized conversion efficiency in 60-GHz band. By reducing P-N junction capacitance in the avalanche photo-detection region and parasitic n-well/substrate capacitance, the supplied 30-GHz LO is efficiently converted to the 60-GHz harmonic LO signal and generates up-converted RF signals from optical IF. In addition, the silicide layer under the metal contact reduces the parasitic resistance and enhances the mixer conversion efficiency.**

I. INTRODUCTION

There are growing research interests for millimeter-wave wireless systems. In particular, the 60-GHz band is very attractive for short range high-speed wireless networks such as wireless personal area network (WPAN) and wireless local area network (WLAN) due to the wide bandwidth of about 7-GHz it can provide. However, the wireless coverage of the millimeter-wave communication is limited to a few meters due to the large transmission loss in the air. Consequently, a large number of antenna base stations and effective distribution networks are required for implementation of WLAN in the millimeter-wave band.

The fiber-fed millimeter-wave wireless system is an attractive technology that can simplify the antenna base stations and reduce the overall cost [1-3]. Especially, the remote up-conversion scheme can reduce the burden of high-speed optical component [3]. In this system, broadband data signals are optically distributed from central station to antenna base stations via optical fiber, and then frequency converted to millimeter-wave band in antenna base station for transmission to mobile terminals through wireless link. In this scheme, optoelectronic mixer (O/E mixer) is the key device in antenna base station with multi-functionality of photo-detection and frequency conversion of optical IF to RF signals [4-7].

The several types of O/E mixer have been reported that are based on InP high-electron mobility transistor [4], InP heterojunction bipolar transistor (HBT) [5], or CMOS-compatible avalanche photodiode (CMOS-APD) [6-7]. The InP-based O/E mixers offer good photo-detection and frequency conversion efficiencies which allow utilization of the optically distributed local oscillator (LO) from central station in great simplification of antenna base stations [5]. However, InP technologies are not cost effective for wide commercial applications as of yet. In contrast, optoelectronic mixers based on CMOS technology has the capacity for integration of optoelectronic devices with powerful CMOS circuits. In addition, CMOS-based photo-detectors can detect 850nm light, allowing the use of multi-mode fiber (MMF) and a vertical-cavity surface-emitting laser (VCSEL), which can further enhance the system cost effectiveness.

However, CMOS-APD O/E mixers have relatively poor photo-detection and frequency conversion efficiency compared to InP-based O/E mixer, which directly affects on the optical sensitivity of the antenna base station. In order to reduce this problem, we performed optimization for conversion efficiency for CMOS-APD 60-GHz band harmonic O/E mixers and the results are presented in this paper.

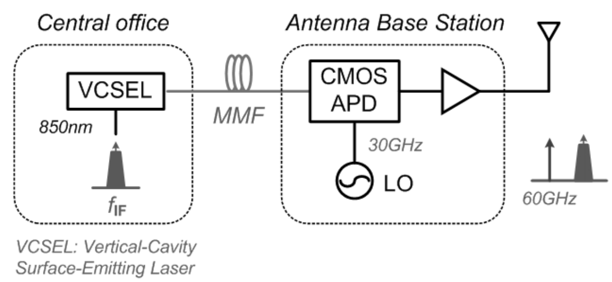

Figure 1. Schematic diagram of fiber-fed 60-GHz wireless system based on CMOS APD O/E mixer

I. OPERATION PRINCIPLE OF CMOS APD O/E MIXER

Fig. 1 shows the schematic of fiber-fed 60-GHz wireless system based on CMOS-APD O/E mixer. In this system,

978-1-4244-7825-5/10/$26.00 ©2010 IEEE

optical IF signals are generated in the central station using low-cost VCSEL and transmitted to the antenna base station through MMF. In the antenna base station, the optical IF signals are photo-detected and harmonically frequency up-converted to 60-GHz band by CMOS-APD O/E mixer using 30-GHz LO. Then frequency up-converted RF signals are radiated to mobile terminals through the wireless channel.

The cross-section of a CMOS-APD O/E mixer fabricated with 0.13μm standard CMOS process is shown in Fig. 2. Vertically injected optical IF signals are photo-detected by the vertical P-N junction between P+ and N-well regions [8]. The resulting photo-currents are collected by multi-finger electrodes on P+ region so that slow diffusion currents generated in the N-well/P-substrate junction are blocked. ADPs having two different lateral dimensions, 10X10 μm^2 and 30X30 μm^2, are characterized.

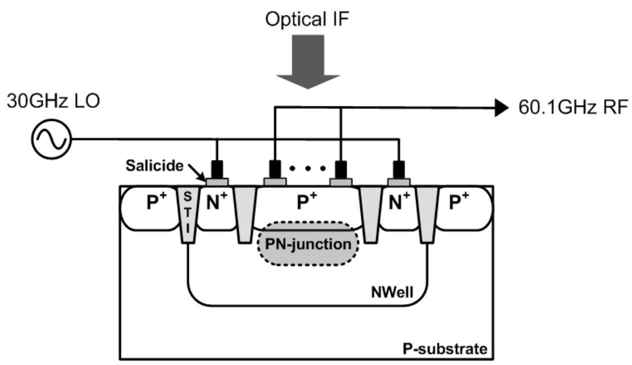

Figure 2. Cross-sectional structure of CMOS APD and O/E mixer configuration

II. PHOTO-DETECTION CHARACTERISTICS

Fig. 3 shows dc photo-currents of the fabricated CMOS-APDs with different active areas of 10X10 μm^2 and 30X30 μm^2, when optical power of 0dBm is injected through lensed fiber of 10um spot diameter. The optical responsivity strongly depends on the reverse bias voltage because the avalanche multiplication gain is determined by the electric field applied to the P-N junction [8]. The measured optical responsivities of 10X10 μm^2 and 30X30 μm^2 devices are comparable. This means that both of the photo-detection efficiency and avalanche gain are not significantly affected by the device size. The peak avalanche gain for 10X10 μm^2 and 30X30 μm^2 devices are 112 and 121, respectively, at reverse bias voltage of 10.3V.

Fig. 4 shows the photo-detection frequency response measured at reverse bias voltage of 10.25V where the response is largest. The incident optical power is 0dBm. As can be seen, 10X10 μm^2 APD has much larger bandwidth (BW_{-3dB}=5.75GHz) than 30X30 μm^2 APD (BW_{-3dB}=2.1GHz). It's mainly due to the reduced RC time constant of the smaller device with smaller junction capacitance.

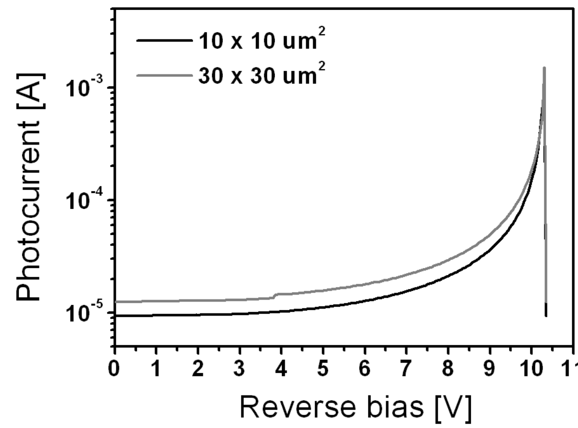

Figure 3. DC photo-current of the CMOS APD as a function of reverse bias voltage applied in N-well. Incident optical power is 0dBm

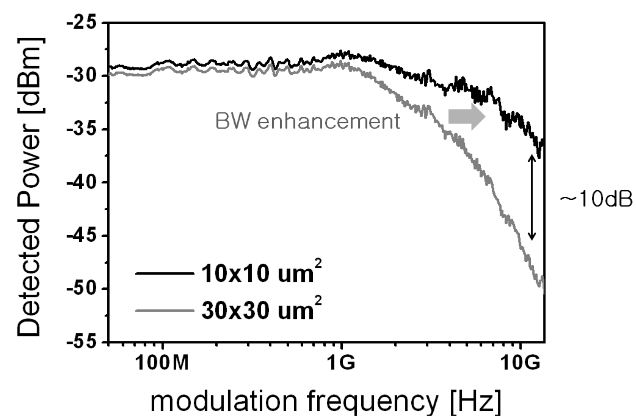

Figure 4. Photo-detection frequency response of CMOS APD at reverse bias voltage of 10.25V and incident optical power of 0dBm

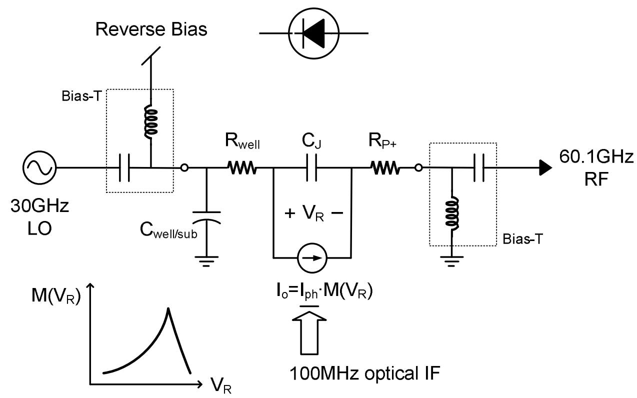

Figure 5. Equivalent circuit model desciption of CMOS APD-based harmonic O/E mixer

III. CONVERSION EFFICIENCY OPTIMIZATION

For O/E mixing operation, 30-GHz LO is applied to N-well of the APD as shown in Fig. 2, which modulates the input optical IF signals to generates 60-GHz RF signals. The detailed operation is described in Fig. 5 with an equivalent circuit model for the APD. In this model, the output photo-current of APD is a product of the primarily photo-detected current of optical IF (**I_{ph}**) and the avalanche multiplication gain (**M**) which is a function of the reverse bias voltage across the P-N junction (**V_R**). So, when 30-GHz LO signals are applied to the APD, the nonlinearity of multiplication gain for **V_R** generates 2^{nd} order harmonic LO in 60-GHz and also RF signals in 60.1-GHz by modulation of the 100-MHz optical IF signals.

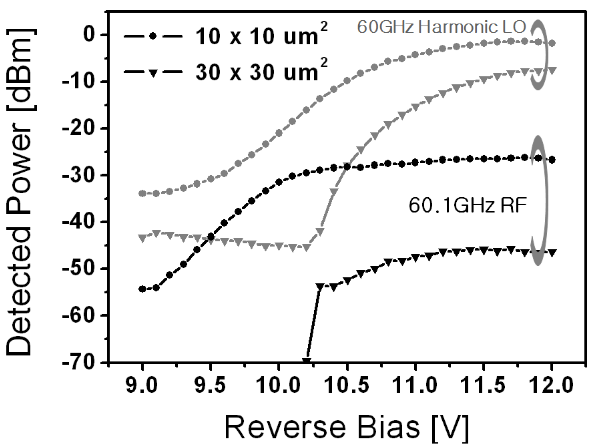

Figure 6. Measured power of 60-GHz harmonic LO and 60.1-GHz frequency up-converted RF signal when the APD size is 10X10 um^2 and 30X30 um^2 seperately. The incident optical power is 0dBm.

In high frequencies such as 30-GHz, however, the junction capacitance (**C_J**) exhibits very low impedance which is inversely proportional to frequency. Consequently, a large portion of the supplied LO power passes the P-N junction through the junction capacitance and only a small portion of the supplied LO remains as the voltage swing across the intrinsic P-N junction (**V_R**) resulting in conversion efficiency degradation. In addition, the parasitic capacitance between N-well and P-substrate (**$C_{well/sub}$**) causes power loss of the high frequency LO. These losses of LO by junction capacitance and parasitic capacitance can be easily improved by reducing the lateral size of the APD. Fig. 6 shows the measured powers of 60-GHz harmonic LO and 60.1-GHz frequency up-converted signals from the APDs of different size. The 10X10 μm^2 APD has minimum 20 dB larger conversion efficiency than the 30X30 μm^2 device.

The parasitic resistances such as N-well resistance or P+ contact resistance also can degrade the O/E mixing efficiency. Fig. 7 shows comparison of conversion efficiencies between 10X10 μm^2 APDs for which P+ contacts are formed with and without the silicided layer. The silicided layer reduces P+ contact resistance from few ohms to nearly zero. Even though the silicided layer does not affect the photo-detection characteristics, for O/E mixing operation, the APD with silicided layer has from 7 to 17dB larger conversion efficiency than the one without silicided layer.

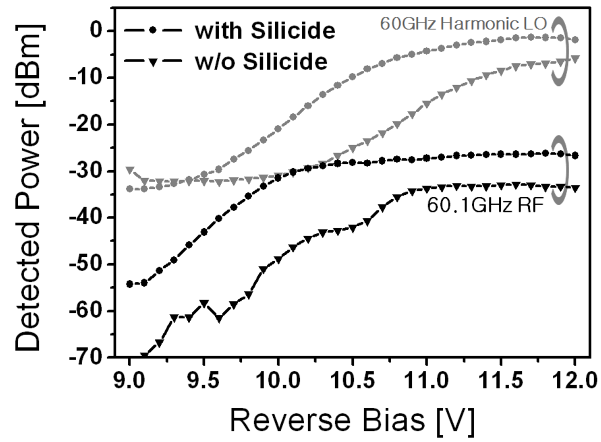

Figure 7. Measured power of 60-GHz harmonic LO and 60.1-GHz frequency up-converted RF signal when P$^+$ contact of the APD is formed with and without salicided layer. The APD size is 10X10 um^2 and the incident optical power is 0dBm.

IV. CONCLUSION

The CMOS-APD 60-GHz harmonic optoelectronic mixers are investigated for conversion efficiency enhancement. By reducing the junction capacitance and parasitic losses, the 2^{nd} order LO and frequency up-converted signal power can be significantly improved. In addition, down-sizing of the APD can improve the photo-detection bandwidth for optical IF detection maintaining the optical responsivity. The resulting frequency conversion loss of the optimized 60-GHz O/E mixer is about 1.5dB.

ACKNOWLEDGMENT

This work was supported by the Seoul Development Institute under the Seoul R&BD Program (NT080542). The chip was fabricated through the MPW of IC Design Education Center (IDEC) supported by the Korea Ministry of Knowledge Economy (MKE).

REFERENCES

[1] A. J. Seeds, “Microwave photonics,” IEEE Trans. Microw. Theory Tech., vol. 50, no. 3, pp. 877–887, March 2002.

[2] G. H. Smith and D. Novak, “Broadband millimeter-wave fiber-radio network incorporating remote up-down conversion,” IEEE MTT-S Int. Microw. Symp. Dig., Baltimore, MD, pp. 1509-1512, June 1998.

[3] H. Ogawa, D. Polifko and S. Banba, “Millimeter-wave fiber optics systems for personal radio communication,” IEEE Trans. Microw. Theory Tech., vol. 40, no. 12, pp. 2285-2293, December 1992.

[4] 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, January 2005.

[5] 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, December 2005.

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

[7] M. J. Lee, H. S. Kang, K. H. Lee and W. Y. Choi, "Self-Oscillating Harmonic Opto-Electronic Mixer Based on a CMOS-Compatible Avalanche Photodetector for Fiber-Fed 60-GHz Self-Heterodyne Systems," IEEE Trans. Microw. Theory Tech, vol. 56, no. 12, pp.3180-3187, December 2008.

[8] H. S. Kang, M. J. Lee and W. Y. Choi, "Si avalanche photodetectors fabricated in standard complementary metal-oxide-semiconductor process," Applied Physics Lett., vol. 90, 151118, April 2007