Millimeter-wave Optoelectronic Mixers Based on CMOS-Compatible Si Photodetectors

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***Abstract* — We present millimeter-wave optoelectronic mixers based on Si photodetectors fabricated by the standard 130 nm complementary metal-oxide-semiconductor (CMOS) process. The photodetector and optoelectronic mixer characteristics are investigated in order to optimize their performances. Using the avalanche process in photodetectors at high reverse bias voltages, efficient optoelectronic mixing with low conversion loss at 30 GHz band is obtained. In order to demonstrate the feasibility of applying this mixer for Radio-on-fiber (RoF) applications, detection and frequency up-conversion of optical 5 MS/s, 16 quadrature amplitude modulation (QAM) signals into the 30 GHz band is successfully performed. We believe this is the first report of using CMOS-compatible photodetectors for RoF applications.**

***Index Terms* — Avalanche process, CMOS compatible photodetector, microwave photonics, optoelectronic mixer, Radio-on-fiber systems.**

I. INTRODUCTION

In millimeter-wave radio-on-fiber (RoF) systems, broad-band data and/or high-frequency signals are distributed to many base stations through optical fiber and then radiated to free-space using antennas. As a consequence, simple and low-cost implementation of base stations is very important. For this, several approaches have been reported. For the remote up-conversion method, optical devices and phototransistors have been utilized for simplifying the base station architecture. Cascaded semiconductor optical amplifier (SOA) - electroabsorption modulator (EAM) configuration can perform frequency up and down conversions using SOA cross-gain modulation, photodetection and nonlinearity of EAM [1]. Phototransistors based on InP high electron-mobility transistors (HEMTs) and heterojunction phototransistors (HPTs) have been also investigated because they can simultaneously provide photodetection, amplification and frequency mixing [2, 3]. Although these approaches can significantly simplify the base station architecture, InP-based components are, as of yet, not very cost-effective.

In another approach, photodetector nonlinearity has been used for photodetection and frequency mixing. Frequency up or down conversion using GaAs metal-semiconductor-metal photodetectors (MSM-PD) [4], InGaAs p-i-n photodiodes [5] or Si avalanche photodiodes (APDs) have been reported [6, 7]. However, the optoelectronic mixers based on theses photodetectors require output signal amplification to compensate conversion loss and it is not an easy task to integrate these photodetectors with necessary electronic circuits in a cost-effective manner.

CMOS optoelectronics is a very promising technology for solving these problems. CMOS technology is widespread and mature and possesses great potential for cost reduction. In addition, it provides a powerful platform in which many necessary circuits can be easily integrated. However, using CMOS for microwave photonic applications has not been actively pursued until now.

Since silicon can detect light in the wavelength range of about 850 nm, photodetectors fabricated by CMOS process have been actively pursued [8]. With the readily available low-cost AlGaAs/GaAs vertical-cavity-surface-emitting lasers (VCSELs), low-cost and high volume optical links can be achieved. In addition, with the recent development of millimeter-wave CMOS circuits [9], the System-on-Chip (SoC) approach for RoF systems provides great potential for millimeter-wave RoF applications.

As a first step for realizing such potential, we investigate millimeter-wave CMOS-compatible OptoElectronic Mixer (CMOS-OEM) fabricated by the standard 130 nm CMOS process. We demonstrate that CMOS-OEM can detect optical 5 MS/s 16 QAM baseband signals and frequency up-convert them into the 30 GHz band.

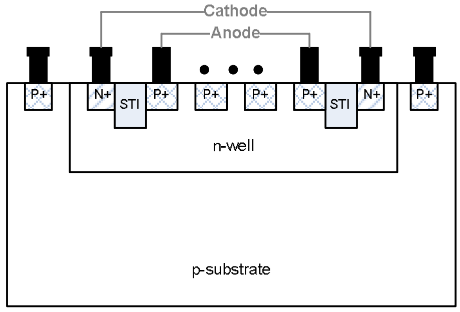

Fig. 1. Schematic cross-section of fabricated photodetector.

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II. PHOTODETECTOR STRUCTURE

Fig. 1 shows the cross-sectional diagram of the fabricated photodetector. In order to eliminate the slow diffusion currents in the substrate region, we use PN junctions between P+ source/drain diffusion and n-well regions [10]. Interdigitated P+ diffusion regions with 1.6 μm are formed to enhance responsivity [8]. The photodetector active area is about 30×30 μm^2 and the salicide process is blocked for the optical window.

III. PHOTODETECTOR CHARACTERISTICS

For the photodetector characterization, 850 nm optical signal from a Fabry-Perot LD was injected to the device using a lensed-fiber. Fig. 2 shows I-V characteristics with and without optical illumination. The incident optical power was 3.7 mW measured at the end of the lensed fiber. In Fig. 2, the avalanche breakdown can be observed at the reverse bias voltage of about 9.4 V.

For measurement of optical modulation frequency response, a 20 GHz electro-optic modulator and a vector network analyzer were used. Fig. 3 shows optical modulation responses of the fabricated photodetector at different bias voltages. When the applied reverse voltage increases, the responsivity of the photodetector increases as the bias voltage approaches the reverse breakdown voltage. At the reverse bias voltage of 9 V, 3-dB bandwidth of fabricated photodetector is about 1.9 GHz. Above the reverse breakdown voltage, the modulation response shows a roll-off in the low frequency region. The decaying modulation response is believed due to the avalanche gain process, whose speed is limited by the avalanche build-up time. In spite of this roll-off, there is a flat response region of a few hundreds MHz at the frequency above 300 MHz. This is the region used for our investigation since CMOS-OEM in this region provides reasonable responsivity as well as the required nonlinearity for mixing.

IV. IMPLEMENTATION OF OPTOELECTRONIC MIXER

Frequency up-conversion using CMOS-OEM is implemented in the manner shown in Fig. 4. Electrical LO signal is injected to the cathode port, which is tied to n-well contact and modulated optical IF signal is illuminated to the device. Up-converted signal is taken out from the anode port to eliminate the slow diffusion

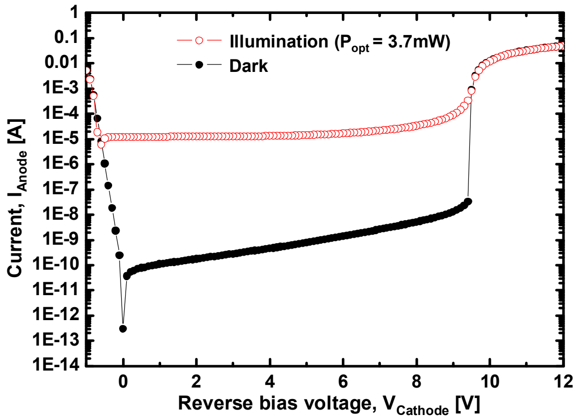

Fig. 2. Current-voltage (I-V) characteristics of the photodetector under dark and illumination condition. The incident optical power is 3.7 mW.

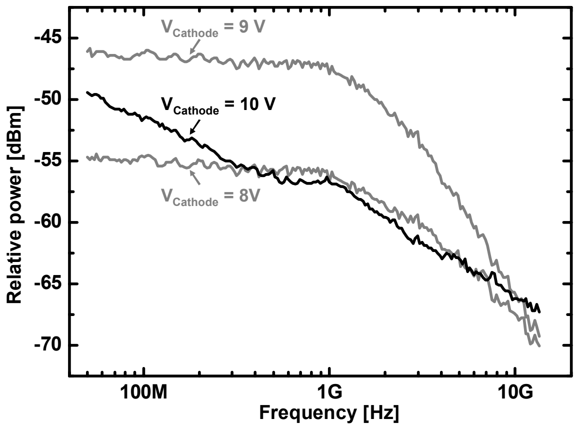

Fig. 3. Optical modulation response of photodetector at different bias voltages.

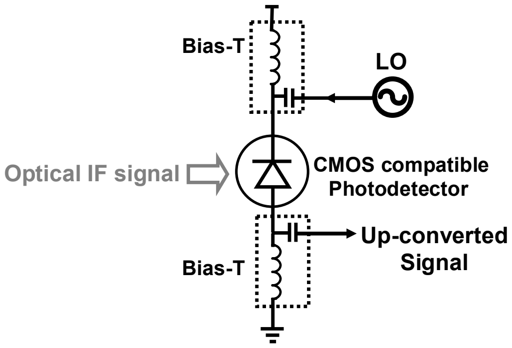

Fig. 4. Schematic diagram of frequency up-conversion using CMOS-compatible photodetectors.

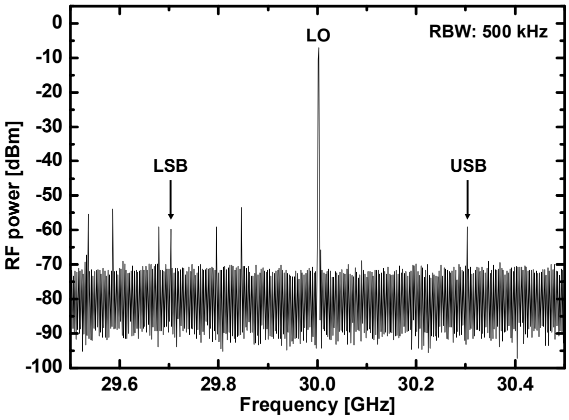

Fig. 5. Frequency up-converted signal spectrum when 30 GHz electrical LO and 300 MHz optical IF signals are injected to the device.

components in substrate region. With the help of nonlinear characteristics of photodetectors due to the avalanche process [6,7], CMOS-OEM can perform photodetection and frequency conversion simultaneously.

Fig. 5 shows the up-converted signal spectrum of CMOS-OEM when 30 GHz electrical LO and 300 MHz optical IF signals are applied to the device. Upper side band (USB) at 30.3 GHz and lower side band (LSB) at 29.7 GHz are clearly observed. In Fig. 5, other peaks around LSB are due to image signals caused by an external harmonic mixer (HP 11970A) used for our measurement.

In order to characterize and optimize CMOS-OEM, bias voltage dependence of up-converted (USB) and photodetected signal (optical IF) powers were measured and the results are shown in Fig. 6. As the reverse bias voltage increases, frequency up-converted signal power increases owing to enhanced nonlinearity at the bias above the reverse breakdown voltage. On the other hand, the photodetected power of optical IF signal has the maximum value at the reverse breakdown voltage and abruptly decreases when the bias voltage goes beyond the breakdown voltage. This reduction is attributed to the change in modulation response due to the avalanche gain process as shown in Fig. 3.

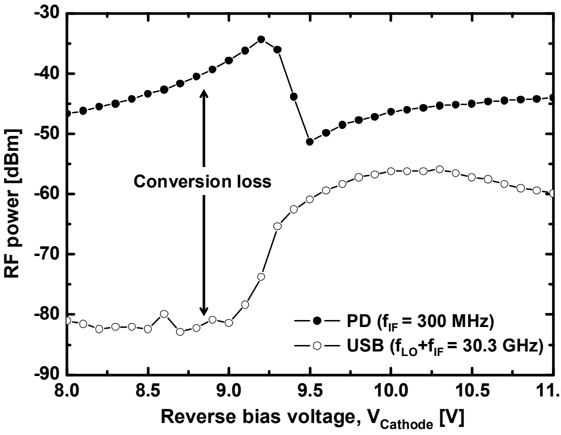

Fig. 6. Photodetected and frequency up-converted signal powers as a function of reverse bias voltage.

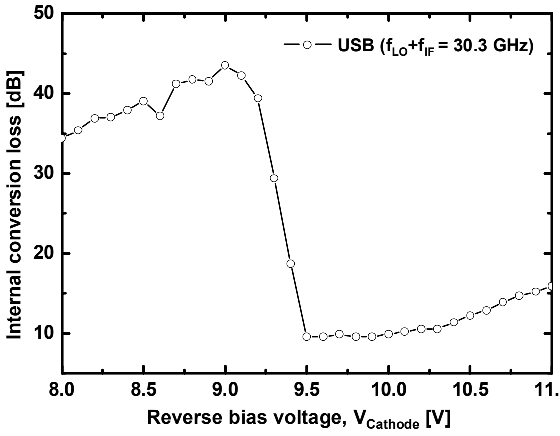

Fig. 7. Internal conversion loss of optoelectronic mixer as a function of reverse bias voltage.

In the optoelectronic mixer, internal conversion loss is an important performance parameter and can be defined as the ratio between the frequency up-converted power and photodetected optical IF power [6, 7]. Fig. 7 shows the estimated internal conversion loss of CMOS-OEM as a function of reverse bias voltages.

V. DATA TRANSMISSION DEMONSTRATION

Utilizing millimeter-wave CMOS-OEM, 30 GHz remote up-conversion downlink RoF transmission was performed. Fig. 8 shows the experimental setup. In the central office, 850 nm light was modulated by 5 MS/s 16 QAM data at 300 MHz IF signal using an EOM and transmitted through 2m standard single-mode fiber. At the antenna base station, optical IF was photodetected and frequency up-converted to 30 GHz band by CMOS-OEM. The revere bias voltage of 10.2 V was used since this provides the maximum frequency up-converted signal power as well as low conversion loss as shown in Fig 6 and Fig. 7. Although this bias voltage is much larger than typical bias voltages used for CMOS circuits, CMOS circuit techniques such as dc-dc up converters [11] can easily solve this problem. The incident optical power at CMOS-OEM was about 4.5 mW. To examine the performance of CMOS-OEM, 30 GHz frequency up-converted data signal was amplified by an amplifier, frequency down-converted by an electric mixer and then analyzed by a vector signal analyzer (VSA). In our experimental setup, LO signal generated by a frequency synthesizer was divided by an RF power splitter and used for both CMOS-OEM and electric mixer. Fig. 9 shows

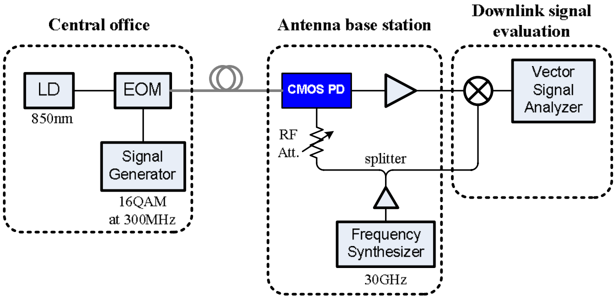

Fig. 8. Experimental setup for 30 GHz downlink data transmission using the CMOS compatible photodetector. LD: laser diode, EOM: electro-optic modulator

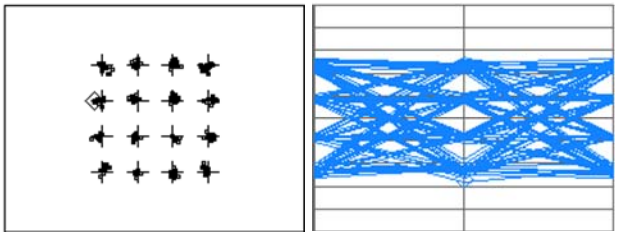
(a) (b)

Fig. 9. (a) Constellation and (b) eye diagram of the demodulated downlink data (16QAM, 5 MS/s) signal.

the constellation and eye diagram of the demodulated 5 MS/s 16 QAM data signal. The measured EVM was approximately 6%, which corresponds to about 24.4 dB SNR.

VI. CONCLUSION

A 30 GHz optoelectronic mixer based on a CMOS compatible photodetector (CMOS-OEM) is implemented and characterized. At the bias voltage above the reverse breakdown, the mixer nonlinearity can be enhanced due to the avalanche gain process resulting in low conversion loss of 10.5 dB at 30 GHz band. Using CMOS-OEM, 5 MS/s 16 QAM data signal was successfully up-converted to 30 GHz and transmitted with 6 % EVM. CMOS-OEM can be easily integrated with other CMOS circuits, and, consequently, provides a possibility for the SoC realization of base stations.

ACKNOWLEDGEMENT

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