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CMOS-Compatible Si Avalanche Photodetectors for Microwave Photonics Applications

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Abstract – We demonstrate that CMOS-compatible Si avalanche photodetectors (CMOS-APD) are very useful for microwave photonics applications. CMOS-APDs are fabricated with 0.18 µm standard CMOS technology. Using the CMOS-APD, radio-over-fiber systems for IEEE 802.11a WLAN are realized. In addition, fiber-supported 60 GHz self-heterodyne systems are implemented by utilizing the CMOS-APD as a harmonic optoelectronic mixer.

I. Introduction
Silicon photodetectors fabricated with CMOS technology have been investigated for short-range optical access networks and optical interconnects applications [1]-[4]. With the continuous evolution of CMOS technology for high integration level and high performance, CMOS process has become the most powerful platform for all kinds of electronic circuits including digital, mixed-mode, and RF applications. Consequently, CMOS-compatible photodetectors can provide a single-chip solution for optical receivers consisting of photodetectors and necessary electronic circuits in a cost-effective manner. We have reported that low responsivity and limited 3-dB bandwidth of CMOS-compatible photodetectors can be overcome by the avalanche effect [5]. We demonstrate in this paper that CMOS-compatible avalanche photodetectors (CMOS-APDs) can be also used for microwave photonics applications.

This paper is organized as follows. Section II describes the structure and photodetection performance of the CMOS-APD. In section III, we demonstrate radio-over-fiber (RoF) systems for 5-GHz band WLAN using the CMOS-APD. The RoF transmission of 20 Mb/s, 16 quadrature amplitude modulation (QAM) signal at 5.805 GHz is successfully performed. Section IV presents the use of the CMOS-APD as a harmonic optoelectronic mixer, which simultaneously performs photodetection and frequency mixing. By utilizing these multi-functions of the CMOS-APD, we implement fiber-supported 60 GHz self-heterodyne systems.

II. CMOS-APD Structure and Photodetection Characteristics
Fig. 1 shows the cross-sectional diagram of the CMOS-APD. We designed and fabricated the device with 0.18 µm standard CMOS technology without any process modification or special substrate. The PN junction consists of P+ source/drain and N-well regions. In order to block slow diffusion current generated in p-substrate region, photocurrents are collected by multi-finger electrodes on P+ region. Details of device structure and characteristics are given in [5].

Fig. 1. Schematic cross section of the fabricated CMOS-APD. From [5].

Fig. 2. Avalanche gain and responsivity of the CMOS-APD as a function of $V_B$. Incident optical power ($P_{opt}$) is 0 dBm.

Fig. 2 shows avalanche gain and responsivity of the fabricated CMOS-APD for 0 dBm optical signal injection. Avalanche gain and responsivity strongly depends on the electric field applied to the PN junction, and they increase as reverse bias voltage ($V_B$) increases. Beyond the maximum avalanche gain voltage, avalanche gain starts to decrease due to the space charge effect and thermal heating [5]. With the maximum avalanche gain of 162, the CMOS-APD provides high responsivity of 0.42 A/W at $V_B$ of 10.1 V.
Photodetection frequency responses at different $V_R$ values are investigated and the results are shown in Fig. 3. When applied $V_R$ increases, photodetected signal power increases owing to increased avalanche gain. The CMOS-APD has 3-dB bandwidth of about 3 GHz at $V_R$ of 10.1 V.

Fig. 3. Photodetection frequency response of the CMOS-APD at different $V_R$. $V_R$ increases from 9.8 V to 10.1 V with the increment of 0.1 V. Incident optical power is -3 dBm.

III. RoF System for 5-GHz band IEEE 802.11a WLAN

Radio-over-fiber (RoF) systems have been regarded as a promising solution for efficient distribution of radio signals using optical fiber [6]-[11], which can extend the coverage of wireless signals. However, the cost of optical components is a serious obstacle for wide deployment of RoF systems. Several reports for realizing cost-effective RoF systems have been made in which vertical cavity surface emitting laser (VCSELs) and multi-mode fiber (MMF) [9]-[11] were used. However, low-cost implementation of RoF receivers is still a challenge. For this, we have proposed the use of CMOS-APD for 5-GHz band WLAN (IEEE 802.11a) RoF systems [12].

Fig. 4 shows schematic diagram for RoF downlink systems. With the CMOS-APD, it is possible to realize a RoF receiver in which a photodetector is integrated with CMOS RF circuits. We demonstrated RoF transmission of 20 Mb/s, 16 QAM signals at 5.805 GHz using the CMOS-APD. The 5-GHz band WLAN signals were generated using a vector signal generator (Agilent E4432B) and IEEE 802.11a WLAN transceiver (MAXIM 2929EV). For optical modulation of WLAN signals, we used an 850 nm laser diode and an electro-optic modulator. For our demonstration, an external modulator was used. However, directly modulated VCSELs [9]-[11] can be used for further cost reduction. Through 3-m long MMF, optically generated WLAN signals were transmitted to a remote antenna unit and injected into the CMOS-APD using a lensed fiber. After photodetection, WLAN signals were amplified by 40 dB and radiated by a 4 dBi gain omnidirectional antenna. After 40-dB loss of 0.5 m wireless link, received signals were frequency down-converted by an IEEE 802.11a WLAN transceiver, and the down-converted signal quality was analyzed by a vector signal analyzer (Agilent 89441A).

Fig. 5 shows the output signal spectrum of the CMOS-APD when 20 Mb/s, 16 QAM data at 5.805 GHz were RoF transmitted. When the incident optical power into the CMOS-APD was 4 dBm, the signal-to-noise ratio (SNR) was above 20 dB. The bias voltage of 10.1 V was optimized for maximum photodetected signal power. Fig. 6 shows the constellation and eye diagram of demodulated data at the vector signal analyzer. The rms EVM of 5.5 % was obtained with the corresponding SNR of about 22.5 dB. In our experiment, the CMOS-APD requires relatively high optical power to attain high SNR value due to the insufficient optic-to-electric conversion efficiency as well as lack of a transimpedance amplifier. Further improvement is expected with an integrated receiver.

Fig. 4. Schematic diagram of RoF downlink data transmission system for IEEE 802.11a WLAN using CMOS-APD. From [12].

Fig. 5. Photodetected signal spectrum of 20 Mb/s 16 QAM data at the output of the CMOS-APD (Point A in Fig. 4). From [12].
IV. Fiber-supported 60 GHz Self-heterodyne System

In order to meet the growing demand for broadband wireless communications, fiber-supported millimeter-wave wireless systems have attracted lots of attention [13]-[17]. However, for the realization of these systems, the cost of optical and millimeter-wave components is a problem. Because high attenuation loss of millimeter-wave signals reduces the coverage of remote antenna units to the pico- or femo-cell range, a large number of remote antenna units are needed. Previously, multifunctional optical components and III-V phototransistors have been used for cost reduction in fiber-supported millimeter-wave systems [13]-[15]. In addition, we have reported 60 GHz harmonic optoelectronic mixers based on CMOS-APDs for low-cost fiber-supported millimeter-wave systems [16]-[17]. In our scheme, the CMOS-APD performs photodetection and frequency mixing simultaneously.

At the output of the CMOS-APD, frequency up-converted data are amplified, and then radiated along with the LO signal. After transmission of wireless link, received data and LO signal at mobile terminal are self-mixed by a square-law device, resulting in down-converted signals without any phase-locked LO and phase-noise degradation [18].

Fig. 7 shows a schematic diagram for the fiber-supported 60 GHz self-heterodyne wireless system. By utilizing the CMOS-APD as a harmonic optoelectronic mixer, optically modulated data from central station are converted to the electrical signal, and frequency up-converted to the 60 GHz band with only a single device.

The harmonic optoelectronic mixing is done by the nonlinear avalanche gain characteristics of the CMOS-APD and detailed description is given in [17]. Fig. 8 shows configuration of the harmonic optoelectronic mixer and its output spectrum when 30 GHz electrical LO and 100 MHz optical IF signals are applied to the device. As can be seen, second harmonic LO at 60 GHz (2fLO), upper side band (USB) at 60.1 GHz (2fLO + fIF) and lower side band (LSB) at 59.9 GHz (2fLO − fIF) are generated.

Fig. 7. Schematic diagram of fiber-supported 60 GHz self-heterodyne system utilizing the CMOS-APD as a harmonic optoelectronic mixer. From [16].

Fig. 8. Configuration of harmonic optoelectronic mixer utilizing the CMOS-APD and the spectrum of harmonic up-converted signal at 60-GHz band.

Fig. 6. Constellation and eye diagram of demodulated data when 20 Mb/s, 16 QAM signals are RoF transmitted with a wireless link. From [16].

Fig. 7 shows a schematic diagram for the fiber-supported 60 GHz self-heterodyne wireless system. By utilizing the CMOS-APD as a harmonic optoelectronic mixer, optically modulated data from central station are converted to the electrical signal, and frequency up-converted to the 60 GHz band with only a single device.
with 30 GHz electrical LO signal. The frequency upconverted signal as well as LO signal at 60 GHz band were transmitted to a mobile terminal, and then frequency down-converted to IF band by a Schottky diode envelop detector followed by a 60 GHz low-noise amplifier. To maximize the harmonic optoelectronic mixing efficiency, the bias voltage of 10.1 V was applied and electrical LO power was set to 20 dBm. Fig. 9 shows constellation and eye diagram of demodulated 25 Mb/s, 32 QAM data. From the experiment, the rms EVM of about 5.1 %, which corresponds to 21.7 dB SNR, was obtained.

Fig. 9. Constellation and eye diagram of demodulated 25 Mb/s, 32 QAM data. From [16].

V. Conclusions
We demonstrate that the CMOS-APD can be used for microwave photonics applications. Using the CMOS-APD in the 5-GHz band WLAN RoF receiver, 20 Mb/s, 16 QAM data at 54 Mb/s are successfully transmitted. Using the CMOS-APD as a harmonic optoelectronic mixer, a fiber-supported 60 GHz self-heterodyne system is demonstrated.

References