Low-Cost Multistandard Radio-Over-Fiber Downlinks Based on CMOS-Compatible Si Avalanche Photodetectors

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***Abstract*—We demonstrate a radio-over-fiber downlink based on a silicon avalanche photodetector (APD) fabricated with 0.18-μm standard complementary metal–oxide–semiconductor (CMOS) technology. An 850-nm vertical-cavity surface-emitting laser is used to deliver multistandard services including 2.1-GHz wideband code-division multiple access and 2.4-GHz IEEE 802.11g wireless local area network signals over 300-m multimode fiber. These signals are successfully detected by a CMOS-compatible APD (CMOS-APD) and then transmitted to a mobile terminal via wireless link. The error vector magnitude performance of each type of signal with the coexisting interferer is investigated.**

***Index Terms*—Avalanche photodetectors (APDs), complementary metal–oxide–semiconductor (CMOS)-compatible photodetectors, complementary metal–oxide–semiconductor (CMOS) technology, multimode fiber (MMF), vertical-cavity surface-emitting laser (VCSEL), wideband code-division multiple access (WCDMA), wireless local area network (WLAN).**

I. Introduction

RADIO-OVER-FIBER (RoF) systems have been widely investigated due to such advantages of optical fiber as low loss, large bandwidth, and transparent characteristics for radio signal transmission. By utilizing RoF systems, various radio-frequency (RF) signals including cellular services and/or wireless local area network (WLAN) signals can be efficiently distributed to densely populated areas or outdoor ranges [1]–[4]. Furthermore, simultaneous RoF transmission of multistandard services has attracted attention because the fiber-optic infrastructure can be shared for multiservices resulting in great system cost reduction [3], [4]. In order to achieve wide deployment of these systems, low-cost realization of optical components and fiber medium is a critical issue. To fulfill the requirement of low-cost implementation, an inexpensive distributed-feedback laser diode [1], vertical-cavity surface-emitting lasers (VCSELs) [2]–[4], and multimode fiber (MMF) [2]–[4] have been investigated. However, these approaches concentrate on the cost reduction for optical sources and transmission media, and no extensive efforts for realization of cost-effective RoF receivers have been reported.

We have demonstrated that cost reduction of RoF receivers is possible using complementary metal–oxide–semiconductor (CMOS) technology [5]–[7]. CMOS technology is the most powerful platform for all types of electronic circuits including digital, mixed-mode, and RF circuits because of low-cost and high-volume manufacturability. Furthermore, Si can detect 850-nm optical signals, and CMOS-compatible avalanche photodetectors (CMOS-APDs) have been realized using standard CMOS technology [8]. Consequently, single chip integration of a photodetector and the necessary RF circuits for RoF receivers is possible on the CMOS platform in a cost-effective manner. For feasibility demonstration of using CMOS-APDs for RoF systems, 20-Mb/s 16 quadratic-amplitude modulation (QAM) data at 5.805 GHz was transmitted via 3-m-long MMF-based RoF downlink [5], [6]. In addition, initial work for RoF transmission of multistandard signals including 2.1-GHz wideband code-division multiple access (WCDMA) and 5.2-GHz IEEE 802.11a over 3-m-long MMF was reported [7]. However, previous RoF systems were implemented with an electrooptic modulator for optical modulation; thus further cost reduction for the optical source as well as a realistic transmission distance is required.

In this work, we demonstrate RoF downlink that uses a CMOS-APD as well as a VCSEL and MMF. We successfully transmit 2.1-GHz WCDMA and 2.4-GHz IEEE 802.11g WLAN signals through the RoF link having a VCSEL, 300-m MMF, a CMOS-APD receiver, and a 2-m wireless link.

II. Experimental Setup

We designed and fabricated the CMOS-APD using 0.18-μm standard CMOS technology without any process modification or special substrate. To overcome the intrinsic problem of low responsivity in CMOS-compatible p-n junction photodetectors, an APD having internal gain is implemented. The fabricated device has high responsivity of 0.7 A/W at a reverse bias of 10.1 V with an avalanche multiplication factor of about 280 under -3-dBm optical illumination. Details of device structure and characteristics are given in [8]. To convert photocurrents generated in the CMOS-APD into voltages with amplification, we fabricated an optical receiver board on which a commercially available transimpedance amplifier (ADN2882 from Analog Devices) was wire-bonded to the CMOS-APD. The transimpedance amplifier had a gain of about 60 dB $\cdot\,\Omega$.

Manuscript received September 12, 2008; revised December 12, 2008. First published February 03, 2009; current version published March 18, 2009. 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 for Information Technology Advancement (IITA).

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Digital Object Identifier 10.1109/LPT.2009.2013356

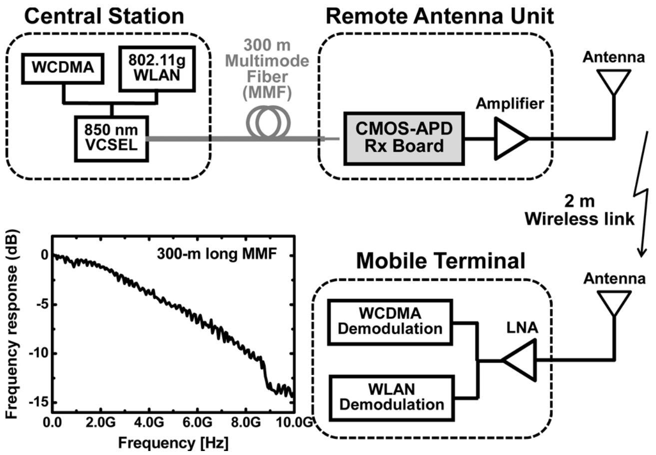


Fig. 1. Experimental setup for RoF downlink data transmission for 2.1-GHz WCDMA and 2.4-GHz IEEE 802.11g WLAN signals. Inset shows frequency response of 300-m-long MMF.

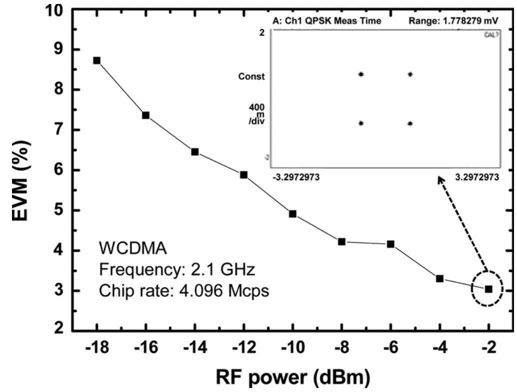


Fig. 2. EVM of demodulated single standard signal of WCDMA as a function of incident RF power to the VCSEL. The inset shows constellation at RF power of −2 dBm.

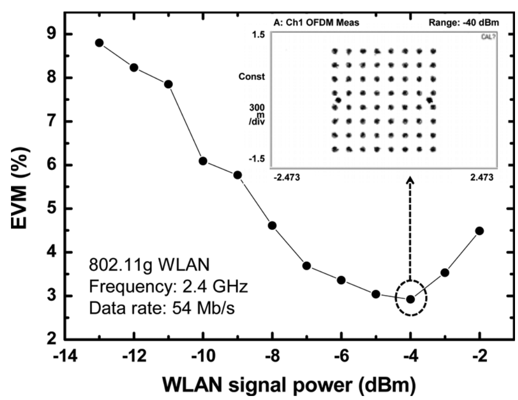


Fig. 3. EVM of demodulated single standard signal of IEEE 802.11g WLAN as a function of incident RF power to the VCSEL. The inset shows constellation at RF power of −4 dBm.

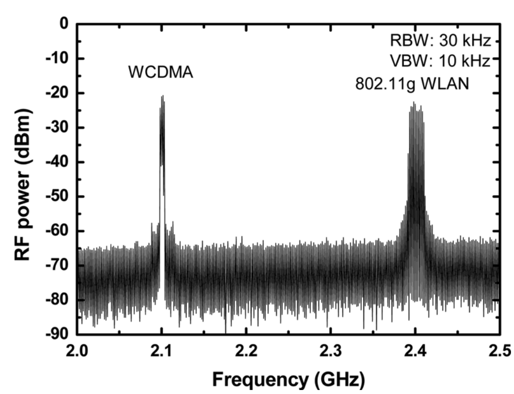


Fig. 4. Output spectrum of amplifier in remote antenna unit when both WCDMA and WLAN signals are RoF transmitted.

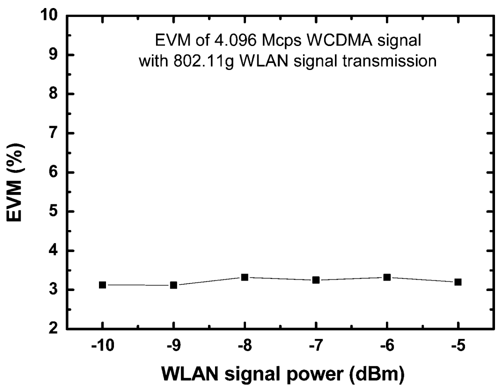
Fig. 1 shows the experimental setup for multistandard signals transmission through RoF downlink. To generate optical signals, a directly modulated 850-nm VCSEL was used at the central station. The multistandard signals, WCDMA at 2.1 GHz and WLAN at 2.4 GHz, were generated using two separate vector signal generators (Agilent E4432B, Anritsu MG3700A) and combined by an RF power combiner (Mini-Circuits ZN2PD-63+). Modulated optical signals were transmitted to the remote antenna unit via 300-m-long MMF whose core size was 50 μm. The measured optical transmission loss of 300-m MMF was about 1.3 dB. The inset of Fig. 1 shows measured frequency response of 300-m MMF. Due to frequency response roll-off of MMF, high-frequency RF signals can suffer from additional loss of RoF link. At the remote antenna unit, transmitted optical signals were injected into the CMOS-APD receiver through a lensed fiber, and after 24-dB amplification by an RF amplifier (Mini-Circuits ZVA-183+), radiated by a 4-dBi omnidirectional antenna. After 2-m wireless link, multistandard RF signals were detected by another 4-dBi omnidirectional antenna, amplified by a 24-dB gain low-noise amplifier, and demodulated by a vector signal analyzer (Agilent 89600). In the experiment, measured signal attenuation of 2-m wireless link including antenna gains at 2-GHz band was about 40 dB. The wireless link distance can be extended with sufficient power amplifier gain to compensate this loss.

III. RoF Downlink Performance

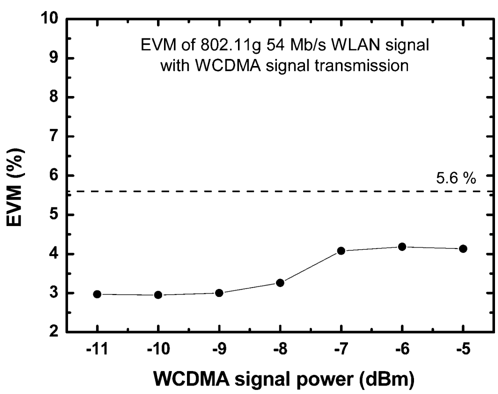
A. Single Standard Transmission

To examine RoF system performance, single standard transmission of 2.1-GHz WCDMA signal was investigated first. Fig. 2 shows the root-mean-square (rms) error vector magnitude (EVM) of demodulated WCDMA signal as a function of input RF signal power to the VCSEL. The chip rate of the WCDMA signal was 4.096 Mcps and the incident optical power at the input of lensed fiber was about −3 dBm. As the input RF signal power increases, the EVM decreases due to the increased optical modulation index. The minimum EVM value of about 3.0% was obtained at −2 dBm, which was the maximum allowed RF power for the VCSEL used in the experiment. The inset of Fig. 2 shows the constellation of demodulated WCDMA signals at RF input power of −2 dBm.

Fig. 3 shows the dependence of rms EVM on input RF signal power when only IEEE 802.11g WLAN signals at 2.4 GHz were applied to the VCSEL. The EVM decreases at first but starts to increase at RF power of −4 dBm. This increase is possibly due to the nonlinearity of VCSEL and CMOS-APD receiver. Because IEEE 802.11g WLAN signals have larger bandwidth than



(a)



(b)

Fig. 5. EVM results of RoF transmission for multistandard signals. (a) EVM of demodulated WCDMA signal as a function of WLAN signal power. (b) EVM of demodulated WLAN signal as a function of WCDMA signal power.

WCDMA, they suffer more from the nonlinearity problem. At the RF power of −4 dBm, the constellation of 64QAM 54-Mb/s OFDM WLAN signals is shown in the inset of Fig. 3.

B. Multistandard Transmission

Both 2.1-GHz WCDMA and 2.4-GHz WLAN signals were applied to the VCSEL and RoF transmitted. Fig. 4 shows the spectrum at the output of amplifier in the remote antenna unit. Each of the WCDMA and WLAN RF signal powers was −5 dBm and the incident optical power at the lensed fiber input was about −3 dBm. The measured signal-to-noise ratio was 44 dB for WCDMA and 33 dB for WLAN signals.

For investigation of signal interference between two types of signals in the RoF downlink, the dependence of EVMs on interfering signal powers was measured and the results are shown in Fig. 5. The RF power of WCDMA or WLAN signals was set to −5 dBm while the interferer power was scanned. The incident optical power at the input of the lensed fiber was set to about −3 dBm.

As can be seen in the figures, WCDMA signals did not suffer any interference from WLAN signals, whereas WLAN suffered when WCDMA signal power became larger. This EVM degradation of WLAN signals is believed due to saturation of the optical receiver and RF components in the remote antenna unit. IEEE 802.11g WLAN signals with larger bandwidth are more sensitive to these undesired effects. Nevertheless, the rms EVM of WLAN signals remains below the 5.6% requirement for data rate of 54 Mb/s as specified in IEEE 802.11g standard [9].

IV. Conclusion

We experimentally demonstrated a low-cost RoF downlink, which includes a VCSEL, 300-m MMF, a CMOS-APD, and 2-m wireless link. The 4.096-Mcps WCDMA at 2.1 GHz and 54 Mb/s IEEE 802.11g WLAN signals at 2.4 GHz are successfully transmitted though the RoF downlink.

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