16-QAM OFDM-Based W-Band Polarization-Division Duplex Communication System with Multi-gigabit Performance

Kwang Seon Kim, Bong-Su Kim, Min-Soo Kang, Woo-Jin Byun, and Hyung Chul Park

This paper presents a novel 90 GHz band 16-quadrature amplitude modulation (16-QAM) orthogonal frequency-division multiplexing (OFDM) communication system. The system can deliver 6 Gbps through six channels with a bandwidth of 3 GHz. Each channel occupies 500 MHz and delivers 1 Gbps using 16-QAM OFDM. To implement the system, a low-noise amplifier and an RF up/down conversion fourth-harmonically pumped mixer are implemented using a 0.1-μm gallium arsenide pseudomorphic high-electron-mobility transistor process. A polarization-division duplex architecture is used for full-duplex communication. In a digital modem, OFDM with 256-point fast Fourier transform and (255, 239) Reed-Solomon forward error correction codecs are used. The modem can compensate for a carrier-frequency offset of up to 50 ppm and a symbol rate offset of up to 1 ppm. Experiment results show that the system can achieve a bit error rate of 10^{-5} at a signal-to-noise ratio of about 19.8 dB.

Keywords: W-band, PDD, OFDM, 10 Gigabit Ethernet, error correction code.

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Kwang Seon Kim (phone: +82 42 860 6683, gskim@etri.re.kr), Bong-Su Kim (bskim1@etri.re.kr), Min-Soo Kang (mskang@etri.re.kr), and Woo-Jin Byun (wjbyun@etri.re.kr) are with the Broadcasting & Telecommunications Media Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Hyung Chul Park (corresponding author, hcpark@seoultech.ac.kr) is with the Department of Electronic and IT Media Engineering, Seoul National University of Science and Technology, Seoul, Rep. of Korea.

I. Introduction

As high-speed wireless data services, such as 3G/4G mobile communications, IEEE 802.11ac/ad wireless LAN, and wired Gigabit Ethernet, are becoming more widespread, multi-gigabit Ethernet networks are needed. Compared to wired multi-gigabit Ethernet networks, wireless multi-gigabit Ethernet networks have the advantage of an easy installation and low construction cost. Many countries are considering allocating the 70 GHz to 90 GHz millimeter wave band for multi-Gbps wireless communications. Many countries have standardized the 71 GHz to 76 GHz and 81 GHz to 86 GHz bands for multi-Gbps wireless communications, including the Republic of Korea, the United States, and the territories of Europe [1]. The United States and Canada recently allocated the 90 GHz band and specified the technical criteria of the 90 GHz band for fixed point-to-point wireless communications. Recent studies presented systems and technologies for 40 GHz, 60 GHz and 70 GHz to 90 GHz band wireless communications [2]-[11]. In previous works, the frequency-division duplex (FDD) scheme [2], [7]-[9] or time-division duplex (TDD) scheme [3]-[4], [9] was used for full-duplex communication. However, the spectral efficiency of full-duplex communication, that is, bidirectional throughput per Hz, is equal to a spectral efficiency of either direction.

This paper presents a 16-quadrature amplitude modulation (16-QAM) orthogonal frequency-division multiplexing (OFDM)-based highly spectral-efficient six-channel 90 GHz band wireless point-to-point broadband communication system. This system can achieve a bit rate of up to 6 Gbps using a

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bandwidth of 3 GHz. In our previous work, we presented a single carrier 16-QAM based E-band (71 GHz to 76 GHz and 81 GHz to 86 GHz) wireless point-to-point broadband communication system [7]. In the previous system, the FDD scheme was used because the spectrum is divided into a lower band (71 GHz to 76 GHz) and an upper band (81 GHz to 86 GHz). However, since a bandwidth of 3 GHz (92 GHz to 95 GHz) is allocated in the 90 GHz band, the proposed system herein utilizes a polarization-division duplex (PDD) architecture to achieve both full-duplex communication and a multi-Gbps data rate. By using a PDD scheme, the spectral efficiency of full-duplex communication can be increased by two times compared to that of the FDD- or TDD-scheme-based existing millimeter wave wireless communication. In addition, an OFDM technique and equalizer are used to reduce the effects of inter-symbol interference caused by multipath propagation.

Table 1. Specifications of proposed system.

Parameter	Specification
Frequency band	92 GHz - 95 GHz
Data rate	6 Gbps
Number of channels	6
Channel spacing	500 MHz
FFT size	256
Subcarrier frequency spacing	1.83 MHz
Modulation	16-QAM
Max. transmit power	10 dBm
Gain (RF transmitter)	16 dB - 21 dB
Gain (RF receiver)	5 dB - 10 dB
Output P1 dB (RF transmitter)	10.5 dB
Noise figure (RF receiver)	< 10 dB

II. System Architecture and Function Blocks

Figure 1 and Table 1 show a block diagram and the specifications of the proposed system, respectively. The proposed system uses a PDD architecture for full-duplex communications. For the PDD, each transmitter and receiver uses an antenna with different polarizations [12]. The transmitter consists of six digital modulators, six quadrature digital-to-analog converters (DACs), six IF up-converters, and one RF up-converter. Each digital modulator generates 16-QAM OFDM signals with a 256-point fast Fourier transform (FFT) and an oversampling ratio of 2. The resolution and sampling rate of the DAC are 12 bits and 781.25 MS/s, respectively. Six IF up-converters upconvert the six modulated signals to the 4 GHz to 7 GHz IF band with a channel spacing of 500 MHz. The RF up-converter upconverts the IF signal and transmits the up-converted signal in the 90 GHz band. The maximum transmission power is 10 dBm. The receiver consists of one RF down-converter, six IF down-converters, six quadrature analog-to-digital converters (ADCs), and six digital demodulators. The RF down-converter down-converts the RF signal to the 4 GHz to 7 GHz IF band. Each IF down-converter down-converts each channel signal to the baseband. The resolution of the ADC is 12 bits, and the sampling rate of the ADC is identical to that of the DAC. Each digital demodulator

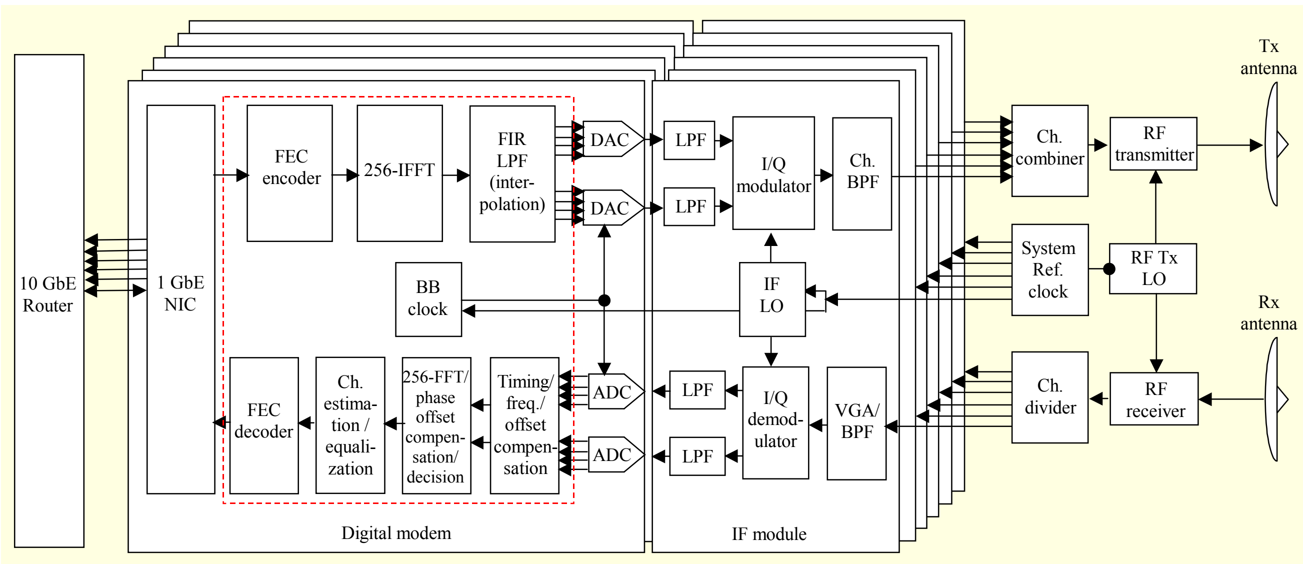

Fig. 1. Block diagram of proposed system.

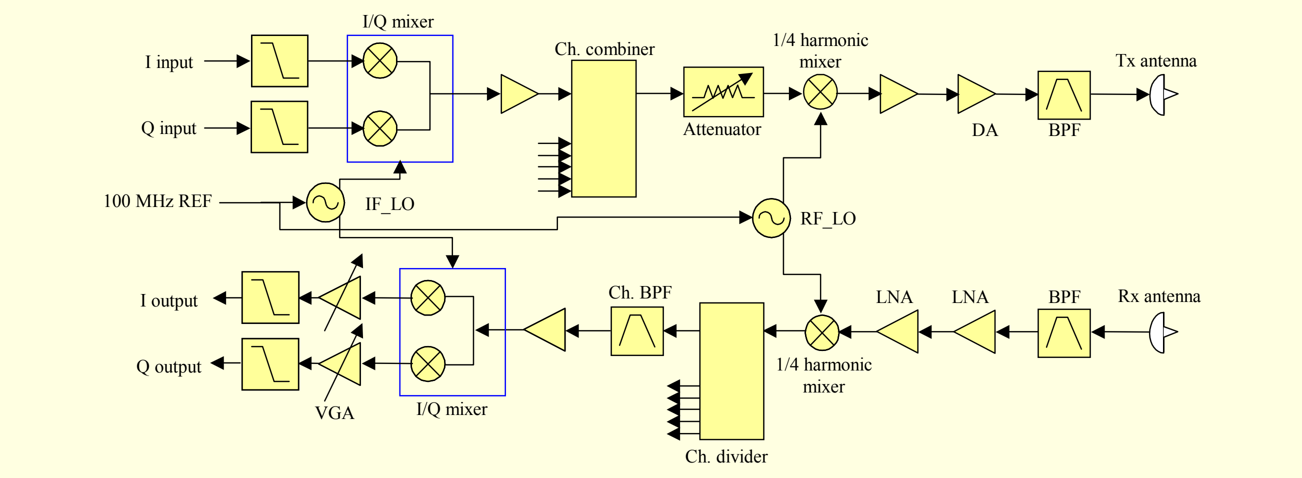

Fig. 2. Block diagram of RF/IF transceiver.

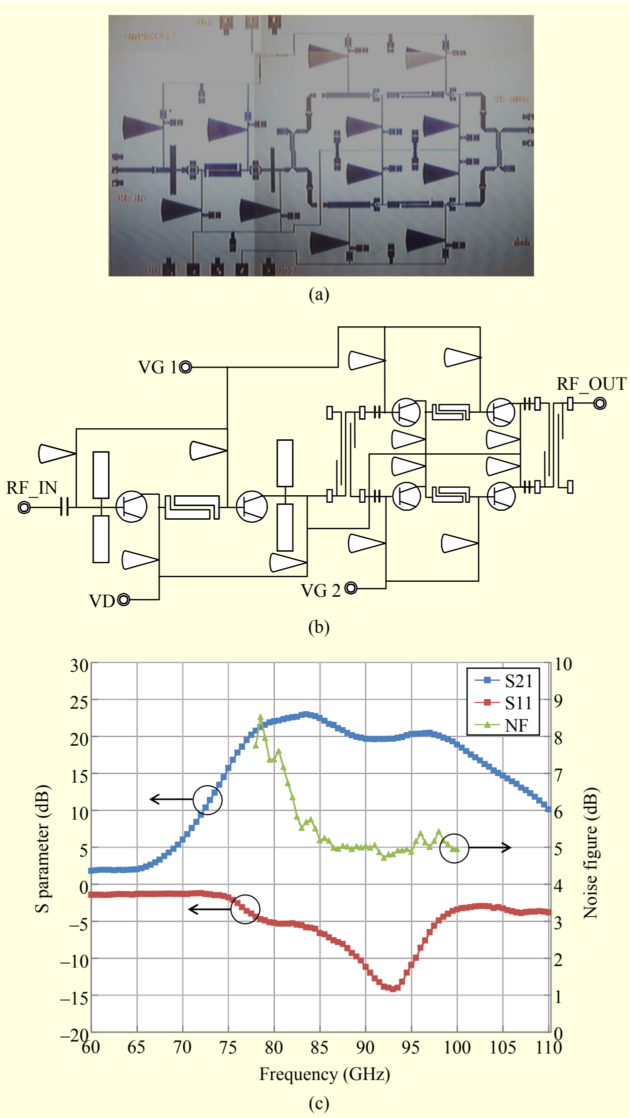

Fig. 3. (a) Chip microphotograph, (b) schematic, and (c) measured results of LNA.

produces 1 Gbps of binary data.

Figure 2 shows a detailed block diagram of the RF/IF transceiver. In the IF transmitter, the digital-to-analog converted signal is low-pass filtered by a seventh-order Butterworth filter with a cutoff frequency of 288 MHz. A passive type I/Q mixer is used for the up conversion, with a conversion loss of 7 dB.

Six IF channel signals are combined for RF transmission. For the RF up conversion, a fourth-harmonically pumped (FHP) mixer and a driver amplifier (DA) are used. The developed system employs a Cassegrain-type antenna with 50 dBi gain. A low-noise amplifier (LNA) and FHP mixer are used in the receiver. In addition, the transmitter and receiver RF mixer are identical. The down-converted signal is divided into six IF signals by a power divider. The channel band-pass filter (BPF) is used to reduce inter-channel interference due to multi-channel signals. The insertion loss of the BPF is less than 2 dB. After channel band-pass filtering and I/Q mixing, an automatic gain control (AGC) is used to maximize the ADC dynamic range while avoiding clipping. The dynamic range of the AGC is 30 dB. The LNA and FHP mixer are designed and fabricated using a 0.1 μm gallium arsenide pseudomorphic high-electron-mobility transistor (GaAs pHEMT) process with a 50-μm wafer thickness, a cutoff frequency of $f_T \approx 120$ GHz, and a maximum oscillation frequency of $f_{max} > 200$ GHz. The LNA uses a combination structure to achieve both a low noise figure and good output matching [13]. In addition, the FHP mixer is designed to lower the local oscillator (LO) frequency and reduce the power consumption [14]. Figures 3 and 4 show chip microphotographs, schematics, and measurement results of the LNA and FHP mixer, respectively. The chip size of the LNA and FHP mixer are 3.6 mm × 2.1 mm and 1.1 mm × 1.0 mm, respectively. Table 2 summarizes the measurement results of the LNA and FHP mixer.

Figure 5 presents a block diagram of the digital modem. A

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Table 2. Measurement results of LNA and FHP mixer.

Parameter		Measurement result
LNA	Gain	> 18 dB
	Noise figure	< 5 dB
	Power dissipation	54 mA @ 2 V
FHP mixer	Conversion loss	16 dB @ up conversion 17 dB @ down conversion
	Input P1 dB	–2 dBm
	LO frequency	20 GHz - 23 GHz

digital modem is implemented in a XC5VSX240T field-programmable gate array. Each data packet is composed of a preamble and physical layer (PHY) payload. The preamble consists of three signal sections. The first of these sections consists of 96 subcarriers in an OFDM symbol, in which each subcarrier is modulated using quadrature phase-shift keying (QPSK) and is used for signal detection and AGC. The second consists of 24 QPSK modulated subcarriers in an OFDM symbol and is used for coarse frequency offset estimation. In addition, the third consists of 96 QPSK modulated subcarriers and is used for fine frequency offset estimation and channel estimation. The PHY payload is modulated using 16-QAM.

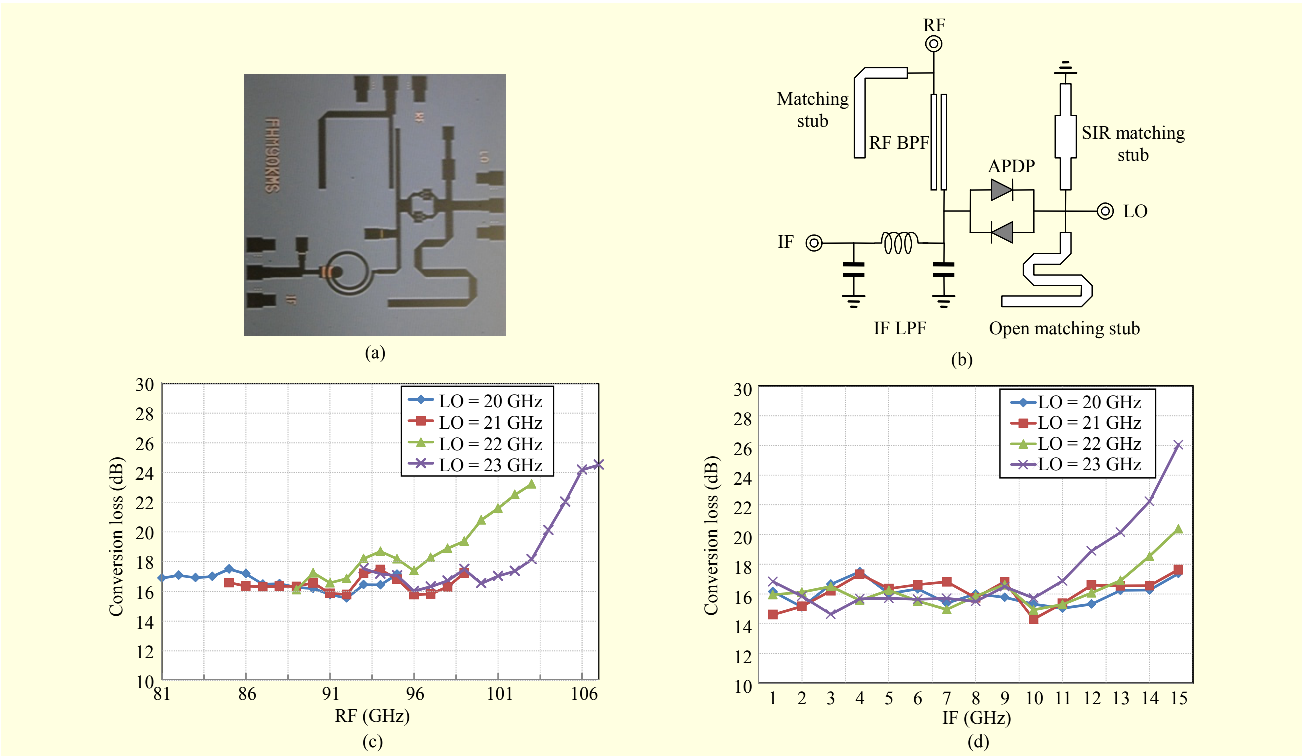

Fig. 4. (a) Chip microphotograph, (b) schematic, (c) measured up-conversion results, and (d) measured down-conversion results of FHP mixer.

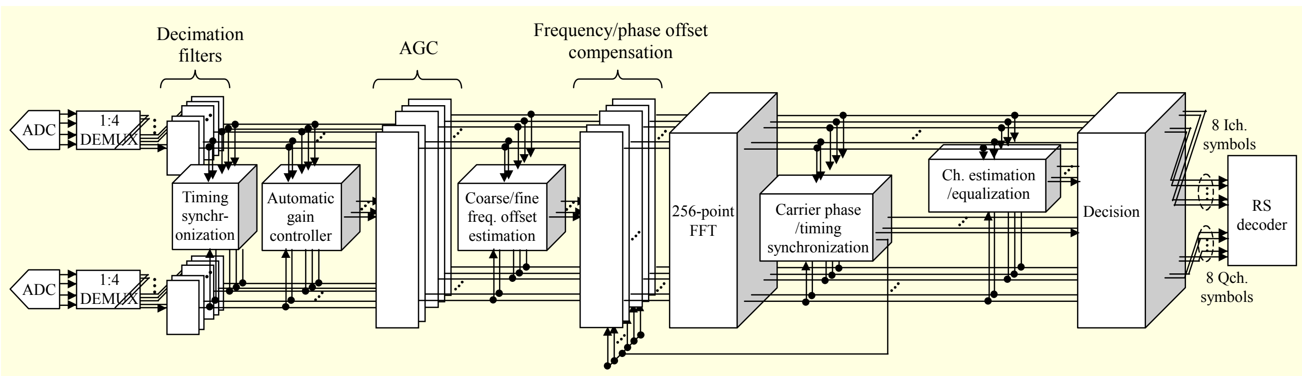

Fig. 5. Block diagram of digital modem.

To reduce the operating frequency of each processing element, parallel processing with multiple function units is used in the modem. In each modulator, four (255, 239) Reed-Solomon (RS) forward error correction (FEC) encoders load 32-bit data simultaneously [6], [15]-[17]. Hence, when the input data rate is equal to 1 Gbps, the output symbol rate in each RS encoder becomes 33.34 Msymbols/sec. Four parallel RS encoded symbols are mapped into eight parallel 4-bit streams by eight 16-QAM mappers. 16-QAM encoded data is fed to a 256-point inverse FFT (IFFT) block. The IFFT output is interpolated by a factor of two using eight digital interpolation filters. Sixteen parallel interpolated samples are converted into four parallel samples using 4:1 multiplexing to utilize the 4:1 multiplexer in the DAC.

In each demodulator, utilizing the 1:2 demultiplexer in the ADC, the two parallel input sample streams are converted into sixteen parallel samples with 1:8 demultiplexing. These samples are decimated by a factor of two. The cross-correlation of the first section of the preamble is used for a digital AGC. Frequency offset compensation is accomplished with the auto-correlation scheme in two steps [18]-[20]. The first step is coarse frequency offset compensation with the second section of the preamble. Through the coarse frequency offset compensation, the residual frequency offset can be reduced to 480 kHz or less from up to 4.5 MHz, that is, 50 ppm. The second step is fine frequency offset compensation with the third section of the preamble. Through the fine frequency offset compensation, the residual frequency offset can be reduced to 80 kHz or less. The residual carrier phase error and symbol timing error are estimated and compensated for by observing the phase rotation of the OFDM subcarriers [21]. In addition, single-tap frequency domain equalization is employed. A least squares algorithm is used to estimate the channel impulse response [22].

III. Experiment Results

Figure 6 shows photographs of the developed system. In Fig. 6(a), the small black box at the top is the RF transceiver and the black box at the bottom is the six-channel IF transceiver and digital modem. The demonstration system

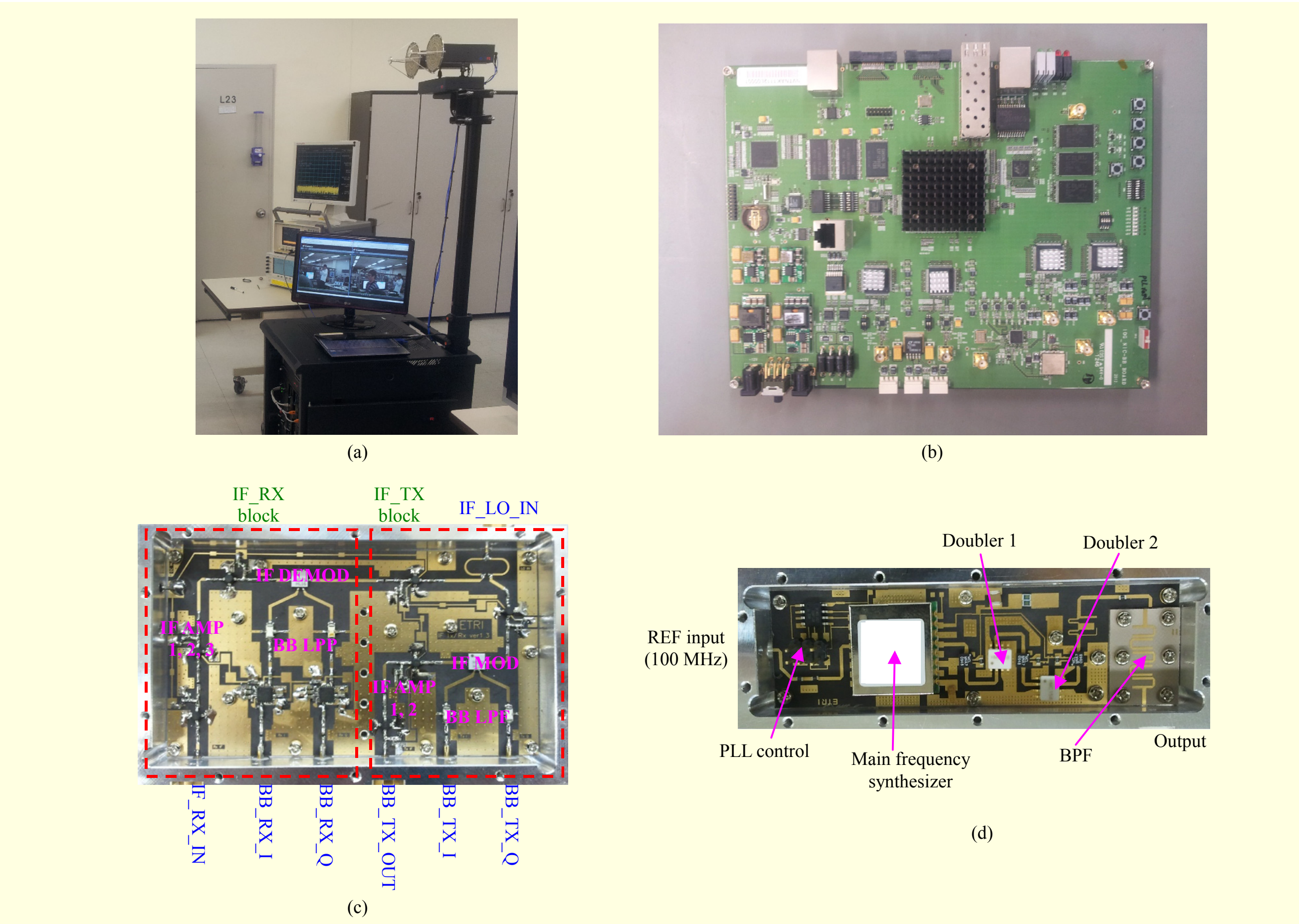

Fig. 6. Photographs of developed system: (a) system setup for demonstration, (b) digital baseband module, (c) IF transceiver module, and (d) IF LO module.

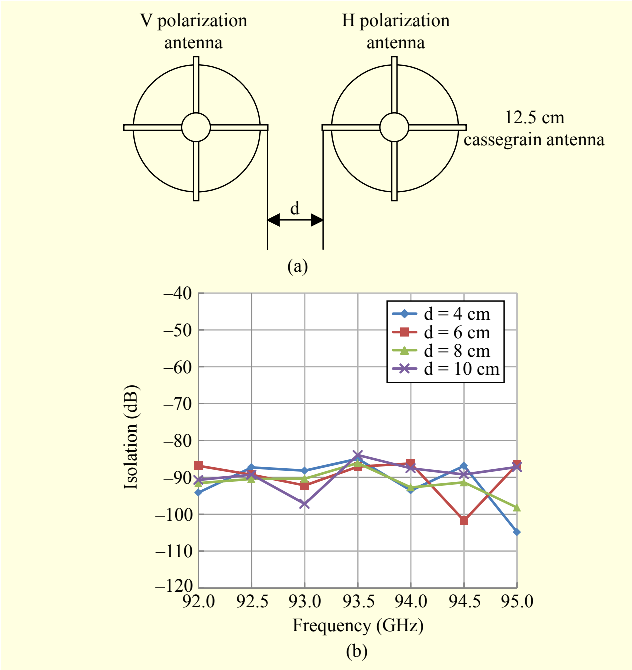

Fig. 7. Measured antenna isolation for PDD: (a) test setup and (b) measured results.

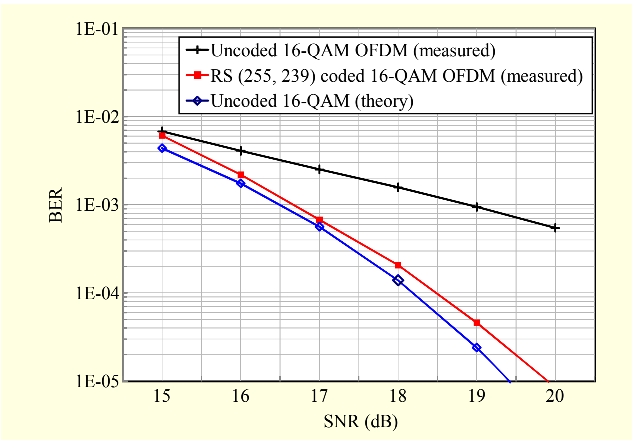

Fig. 8. Measured BER performance.

provides a data rate of 3 Gbps using three channels and uses a Cassegrain-type antenna with a 12.5 cm microstrip reflectarray for an indoor test [23]. The distance between the transmitting and receiving antennas is equal to 4 cm. Figure 7 shows the measurement results of the isolation between the transmittingand receiving antennas. We find that when the distance between the transmitting and receiving antennas is equal to 4 cm, the isolation requirement of 80 dB is satisfied. Figure 8 shows the measured bit error rate (BER) performance.[1)] The system produces a BER of 10^{-5} at a signal-to-noise ratio (SNR) of about 19.8 dB with an RS-FEC code. Uncoded 16-QAM OFDM suffers further performance degradation as compared to the theoretical 16-QAM performance in an additive white Gaussian noise (AWGN) channel. This degradation is caused by implementation loss in the digital modem (about 1 dB) and implementation loss in the 90 GHz band millimeter wave module.

1) To measure the BER performance, the transmitter, receiver, and AWGN signal generator are connected using a cable and an adjustable attenuator is used to sweep the receiver input power.

IV. Conclusion

In this paper, a six-channel 90 GHz band wireless point-to-point broadband communication system with a data rate of 6 Gbps was presented. The system uses 16-QAM OFDM to improve the spectral efficiency and an RS-FEC code to improve the performance. An LNA and an FHP mixer were fabricated, resulting in a noise figure of less than 5 dB and a conversion loss of 16 dB to 17 dB, respectively. The hardware measurement results showed a BER of 10^{-5} at an SNR of about 19.8 dB. If two-foot Tx/Rx antennas are used, the available communication range can be more than 1 km at a rain rate of 42 mm/hr. The developed system is applicable for high-speed wireless networks and wireless home networks as well as wireless backhaul networks.

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Kwang Seon Kim received his BS and MS degrees in electric engineering from Kyungpook National University, Daegu, Rep. of Korea, in 1998 and 2000, respectively. In 2000, he joined ETRI, Daejeon, Rep. of Korea, and worked for the Microwave Technology Research Section as a senior member of the research staff. His research interests are in RF transceiver technology and millimeter-wave systems.

Bong-Su Kim received his BS and MS degrees in information communication engineering from Chungnam National University, Daejeon, Rep. of Korea, in 1999 and 2001, respectively. In 2000, he joined ETRI, Daejeon, Rep. of Korea, where he is currently with the Microwave Technology Research Section of ETRI as a senior member of the engineering staff. His research interests include design and analysis of mm-wave active/passive components and application systems.

Min-Soo Kang received his BS and MS degrees in electric engineering from Sogang University, Seoul, Rep. of Korea, in 1996 and 1998, respectively, and his PhD degree in electrical engineering from Chungnam National University, Daejeon, Rep. of Korea, in 2011. From 1998 to 2000, he was with Hyundai Electronics Industry Co., Incheon, Rep. of Korea, where he developed RF transceivers of base stations for mobile communication. In 2000, he joined ETRI, Daejeon, Rep. of Korea, and worked for the Microwave Technology Research Section as a principal member of the research staff. His current research includes RF circuits and system designs.

Woo-Jin Byun received his BS degree in electronic engineering from Kyungpook National University, Daegu, Rep. of Korea, in 1992 and his MS and PhD degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 1995 and 2000, respectively. In 1999, he joined Samsung Electro-Mechanics Company, Suwon, Rep. of Korea, where he developed mobile communication devices, such as power amplifiers and radio modules for five years. He is

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currently with the Microwave Technology Research Section of ETRI as a project leader of the engineering staff. His current research areas include RF/millimeter-wave/THz integrated circuits and system designs, planar and reflector antennas, and electromagnetic scattering analysis.

Hyung Chul Park received his BS, MS, and PhD degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 1996, 1998, and 2003, respectively. From 2003 to 2005, he was a SoC design engineer with Hynix Semiconductor, Seoul, Rep. of Korea. From 2005 to 2010, he was an assistant professor at the Hanbat National University, Daejeon, Rep. of Korea. In 2010, he joined the faculty of the Department of Electronic and IT Media Engineering, Seoul National University of Science and Technology, Seoul, where he is currently an associate professor. His current research interests include wireless modulation/demodulation algorithms, system design/ implementation, and interface study between RF/IF stages and digital signal processing.