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Xiaodan Pang
Xianbin Yu
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Darko Zibar
Idelfonso Tafur Monroy

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Xiaodan Pang

Xianbin Yu

Technical University of Denmark
DTU Fotonik, DK-2800
Kongens Lyngby, Denmark
E-mail: xipa@fotonik.dtu.dk

Ying Zhao

Tsinghua University
Department of Electronic Engineering
10084, Beijing, China

Lei Deng

Hua-Zhong University of Science and Technology
School of Optoelectronics Science and
Engineering
Wuhan, China

Darko Zibar

Idelfonso Tafur Monroy

Technical University of Denmark
DTU Fotonik, DK-2800
Kongens Lyngby, Denmark

1 Introduction

The seamless convergence of wireless and fiber-optic networks requires wireless links with increased capacity to keep the pace with high-speed fiber-optic communication systems.^{1,2} Millimeter-wave (mm-wave) technology is a promising approach to satisfy the high-capacity requirement for the future wireless access networks. The applications and use of the 60-GHz band are well studied and reported in the literature.^{3,4} Nevertheless, the underexploited higher-frequency range from 100 to 300 GHz is becoming a timely relevant research topic due to its capability to offer an even wider bandwidth for even faster gigabit-class wireless access rate. Recently, many efforts have contributed to achieving data transmission in the *W*-band wireless systems, including mm-wave generation and modulation techniques, transmission performance tests, and analysis.⁵⁻⁷ In most of these works, although they provide details of their experiment configurations, there is limited reported details and studies on the wireless channel characteristics, with less studies considering the combined optical fiber-wireless channel situation. In particular, due to the atmosphere absorption and high free-space loss of mm-wave carrier, the mm-wave wireless transmission distance is highly limited. In this context, the well-known radio-over-fiber (RoF) technology, which integrates optical and wireless systems, provides a solution to increase the coverage while maintaining the mobility of the broadband services in the local area networking scenario.

Abstract. We present a detailed experimental investigation of a hybrid optical-fiber wireless communication system operating at the 75 to 110 GHz (*W*-band) for meeting the emerging demands in short-range wireless applications. Measured *W*-band wireless channel properties such as channel loss, frequency response, phase noise, and capacity are reported. Our proposed system performs a sextuple frequency up-conversion after 20 km of fiber transmission, followed by a *W*-band wireless link. A 500 Mbit/s amplitude shift keying signal transmission is experimentally demonstrated for performance analysis purposes. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.4.045004]

Subject terms: microwave-photonics; millimeter-wave communication; radio-over-fiber; wireless communications.

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In this paper, we experimentally demonstrate a RoF system with a 75 to 100 GHz wireless link. A *K*-band RF signal modulated with data, is up-converted to *W*-band by a six-time frequency multiplier. Using this method, 100-GHz photodetector (PD) and *W*-band amplifiers at the transmitter and receiver, which will increase the operational complexity and system cost, are not needed, as we target short-range high-capacity wireless link with potential reduced complexity. The characteristics of the wireless link are detailed tested and analyzed in terms of frequency response and emission distance. These characteristics are used as basic-considerations for the optimum design of our *W*-band wireless link. Furthermore, up to 500 Mbit/s amplitude shift keying (ASK) data traffic transmission over 20-km optical fiber and 50-cm wireless link is used for our experimental demonstrations and analysis.

2 Experimental Setups

In order to characterize the *W*-band wireless channel, two subsystems are first built, as shown in Fig. 1. The characteristics measurements of the 100-GHz wireless analogue channel are performed in Fig. 1(a). In our experiment, a 12.5 to 18.4 GHz (*K*-band) RF signal is generated, followed by a sextuple millimeter source (Agilent E8257DS15) to up-convert the signal into the 75 to 110 GHz.

After that, a wireless link is established between a pair of *W*-band horn antennas of a 24-dBi gain and less than 4 deg half-power beam width. The receiving antenna is directly connected to a sub harmonic mixer for frequency down-conversion. The local oscillator (LO) signal is 18 times multiplied in the sub harmonic mixer and then mixed with

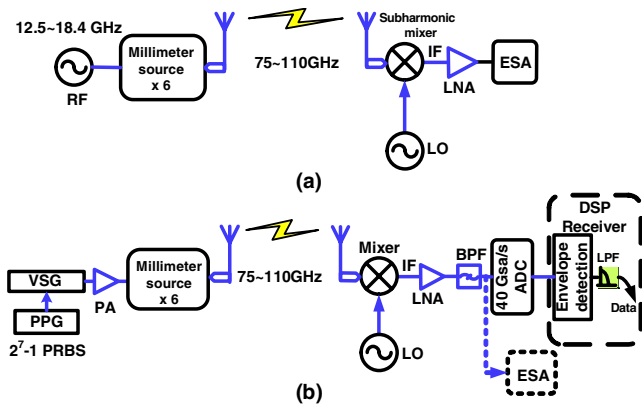


Fig. 1 Schematics of subsystems: (a) *W*-band analogue channel characteristics test; (b) wireless link transmission test (PA: power amplifier, LNA: low-noise amplifier).

the received *W*-band signal. In this way, the *W*-band signals are down-converted to intermediate frequency (IF) at the output of the sub harmonic. Furthermore, a bandpass filter (BPF) is placed after the mixer to filter other harmonics noise due to the imperfect operation of the mixer. Subsequently, the characteristics of the IF signal such as signal power, spectrum, and phase noise are analyzed with an electrical spectrum analyzer (ESA). In the second subsystem as shown in Fig. 1(b), a pseudo random bit sequence (PRBS) of length $2^7 - 1$ is generated by a pulse pattern generator (PPG) and up-converted to *K*-band at a vector signal generator (VSG). The up-converted RF signal is transmitted over the wireless link. The received IF signal is sampled by a 40 Gsa/s analog digital converter (ADC) and then demodulated by a digital signal processing (DSP) receiver using envelop detection scheme.

Figure 2 shows the schematic diagram of our experimental setup of a RoF system including a 75 to 110 GHz wireless link. A DFB laser of 10-MHz linewidth with central wavelength of 1550 nm is fed into a Mach-Zehnder Modulator (MZM) with 15-GHz bandwidth, where a *K*-band RF signal carrying ASK data traffic is intensity-modulated onto the optical carrier. After 20-km non-zero dispersion shifted fiber (NZDSF, NZD+, zero dispersion at 1540 nm) and a low-noise Erbium-doped fiber amplifier (EDFA), the *K*-band RF signal is recovered by a photodiode (PD) before

up-conversion and transmission over the *W*-band wireless link. Similarly, a DSP receiver is used to demodulate the received signals after ADC. It is noted that the 20-km NZDSF and preamp EDFA are used to minimize the impact of fiber dispersion and nonlinear effect on the generated mm-wave signals due to the high nonlinearity of the up-conversion process.

3 Results

3.1 Wireless Link Characteristics

Figure 3 shows the *W*-band channel response by measuring the received IF power as a function of signal frequency in terms of different wireless distances. We can see that, in general, the received power decreases with the increase of RF frequency in a given distance. It also shows that when the two horn antennas are placed close to each other and the wireless distance is assumed to be zero, the received power is significantly decreased in certain RF frequencies. By taking into account the type of antennas used in the experiment, far-field propagation takes places at air distances more than 36.8 cm. Therefore, near-field coupling may introduce such unpredictable behavior.

The relative wireless channel loss as a function of distance is measured and shown in Fig. 4(a). In this measurement, the source RF is set to be 16.6 GHz, corresponding 99.6 GHz after up-conversion. From Fig. 3 it can be seen that at this frequency there is no severe destructive interference at all distances. Because of the complexity of direct measuring the *W*-band RF signal power, the IF power at the receiver is measured based on the linear performance of the LNA. Therefore, the received power at ~0-cm wireless distance is set as a reference level. From the figure it can be seen that the wireless loss increments are 6, 10, and 14 dB when the wireless distance increasing from 1 m to 2, 3, and 4 m, respectively, showing a consistency with the corresponding theoretically calculated values 6.021, 9.542, and 12.04 dB for the same distance increments. The 2-dB difference between the theoretical and measured value for increasing wireless distance from 1 to 4 m is attributed to a slight alignment error when the antenna separation becomes large.

Figure 4(b) shows the impact of the alignment between the transmitting and receiving antennas on the received power. During this measurement the distance between the

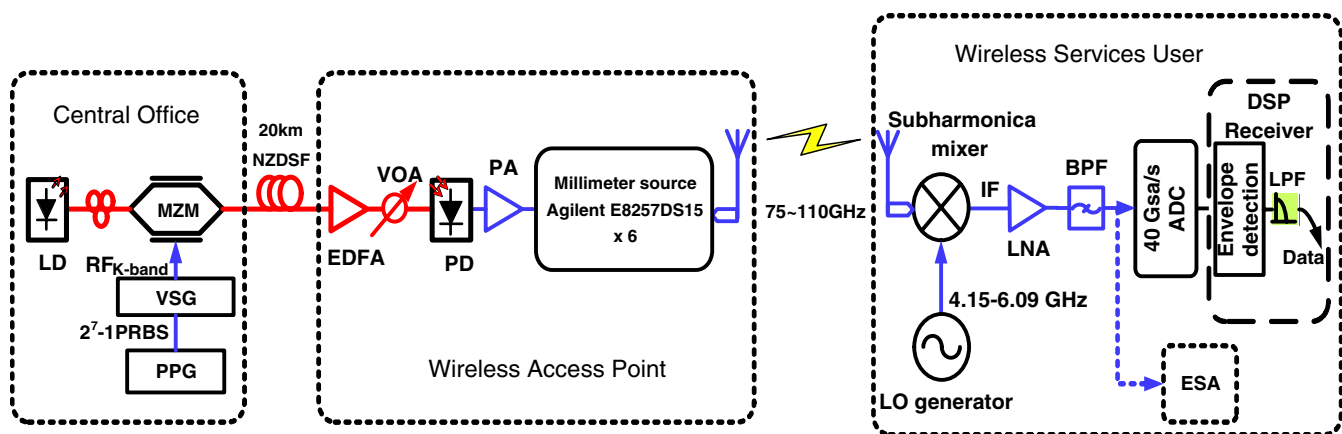


Fig. 2 Experimental setup for a radio-over-fiber system plus a *W*-band wireless link (LD: laser diode, IM: intensity modulator, VOA: variable optical attenuator, PD: photodiode).

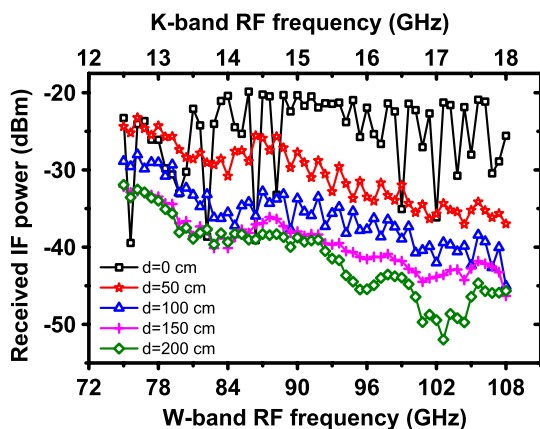


Fig. 3 The W-band channel frequency response in terms of different wireless distances.

two antennas is fixed at 40 cm. We only change the alignment angle between the axes of two antenna's horns to measure the changing of received IF power. It is observed that the ultimate performance of the wireless link is extremely related to the optimum of alignment. From the figure it can be seen that when the alignment angle is increased from 0 to 45 deg, the power penalty in received signal is around 34 dB.

3.2 Wireless Data Transmission

In this subexperiment, the transmission performance of the wireless channel is evaluated. The subsystem setup is shown in Fig. 1(b). According to the Fig. 3, the mixer has the best frequency response when the input RF frequency is 14.6 GHz, which corresponds to the W-band frequency of 87.6 GHz. Moreover, the LO frequency is set to 4.813 GHz, which results in an output IF of 960 MHz (for 1 Gbps transmission, LO is set to 4.803 GHz, corresponding IF is 1140 MHz). However, the transmitted data rate is therefore limited by the narrow bandwidth of the received IF signal. Figure 5 shows the measured bit error rate (BER) performance under different data rates and the wireless distances between the antennas. We begin our measurement from 50 cm distance, at which error-free demodulations are achieved at data rates of 800 Mbit/s and lower, while 1 Gbit/s transmission has a BER of 7.5×10^{-4} . Assuming the forward error correction (FEC) limit of 2×10^{-3} , transmissions at all the measured bit rates are

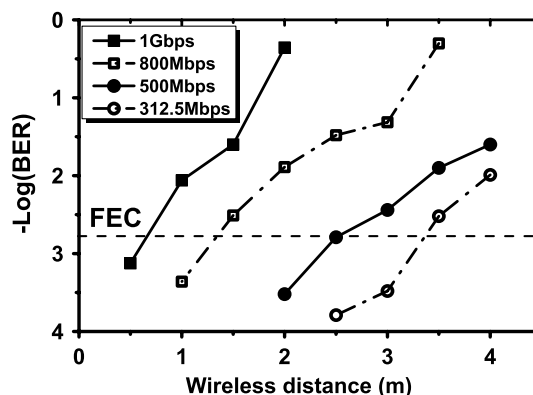


Fig. 5 Measured bit error rate performance against the wireless distance without optical links.

well below this limit. In the experiment, $\sim 10^5$ sampled bits were used to analyze the BER performance offline. Meanwhile, we can notice that as the distance and bit rate increase, the BER performance goes worse.

3.3 Radio-Over-Fiber System

After characterizing the wireless channel properties and the data transmission performance of the W-band link, a RoF experimental system is established. The wireless distance is fixed at 50 cm, and the alignment of antenna's horns is optimized during our measurement. A phase noise characterization is first studied by transmitting a signal frequency RF carrier through the system and compared with the received IF signal after up-conversion and down-conversion. Figure 6 shows the comparison of the phase noise curves between the transmitted and the received RF signal. It can be seen that the phase noise increases approximately $25 \text{ dBc} \cdot \text{Hz}^{-1}$ after the transmission. This is introduced by the frequency nonlinear up-/down-conversions, fiber transmission, and phase noise of the LO signal. From the figure we can also see that the phase noise level of the received IF signal is below $-60 \text{ dBc} \cdot \text{Hz}^{-1}$ between 100 Hz and 1 kHz and well below $-70 \text{ dBc} \cdot \text{Hz}^{-1}$ above 1 kHz. This phase noise floor is considerably well for the demonstrated ASK data transmission at 500 Mbit/s.^{8,9}

System transmission test is demonstrated using the same input RF signal (14.6 GHz, corresponding to 87.6-GHz wire-

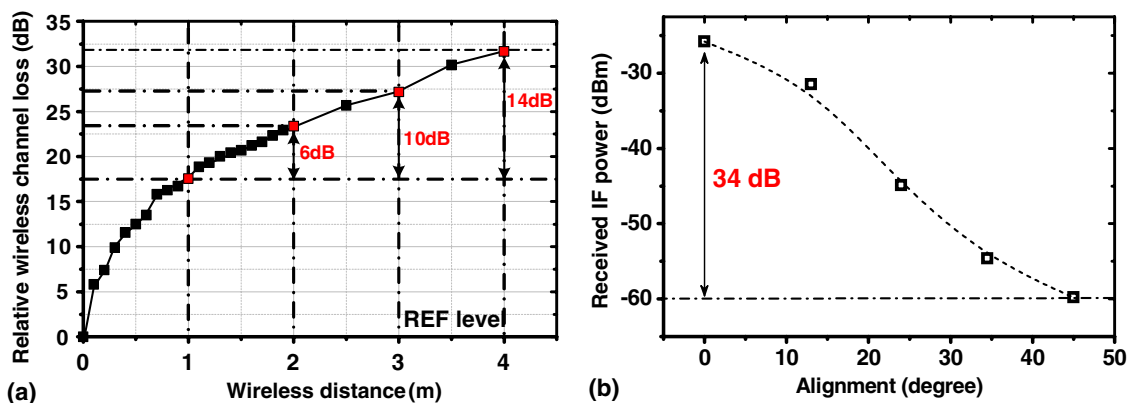


Fig. 4 (a) Wireless channel loss versus wireless distance ($RF_{W\text{-band}} = 99.6 \text{ GHz}$); (b) Received signal power versus alignment between sending and receiving antennas (Source power = 0 dBm, $RF_{W\text{-band}} = 99.6 \text{ GHz}$, wireless distance = 40 cm).

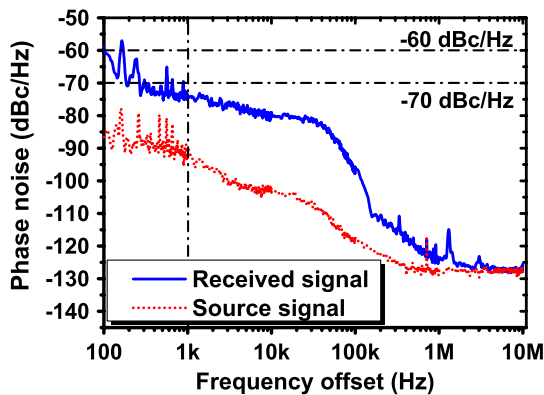


Fig. 6 Measured upper-sideband phase noise of the 14.6-GHz source and up-converted 87.6-GHz signals.

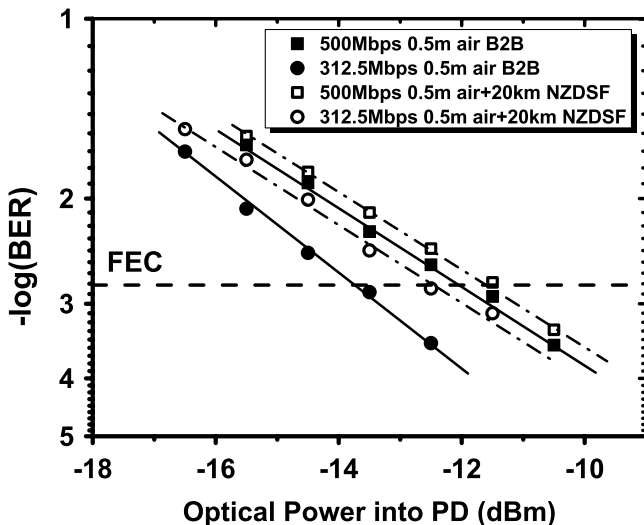


Fig. 7 Measured bit error-rate for 500 and 312.5 Mbps with and without 20-km fiber link transmissions.

less signal) with the previous transmission test in the subsystem [Fig. 1(b)]. In the experiment, the wireless distance is set to 50 cm. The BER performance as a function of the received optical power for 500 and 312.5 Mbit/s data rates in both with and without 20 km fiber transmission are shown in Fig. 7. It can be observed that there was approximately 1-dB receiver penalty between optical back-to-back with 0.5-m wireless transmission and 20-km NZDSF transmission to achieve a BER of 2×10^{-3} .

4 Conclusions

In this report, we experimentally demonstrated a millimeter-wave wireless link operating at 75 to 100 GHz frequency band. Detailed characteristics of this W-band wireless channel were first analyzed in terms of frequency response, phase noise, emission distance, directivity, etc. in order to estimate and optimize the channel performance for data transmission. 3.5 m for 312.5 Mbit/s, and less than 1 m for 1 Gbit/s wireless 100 GHz transmission were successfully demonstrated to achieve BER performance below the FEC limit. Furthermore, by employing the RoF technology, 500-Mbps composite transmission performance over 20-km NZDSF and the wireless channel was also presented. Our results show the importance of

characterizing the hybrid optical-fiber wireless channel for 75- to 110-GHz operation; the data-system experiment shows the potential of high-capacity short-range wireless access systems. Further work is ongoing on comparison of our experimental results and theoretical modeling.

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Xiaodan Pang received a BSc degree in optical information science and technology from Shandong University, Jinan, China, in 2008, and an MSc degree in photonics from Royal Institute of Technology, Stockholm, Sweden, in 2010. He is currently pursuing a PhD degree in optical communications engineering at DTU Fotonik, Technical University of Denmark. His research interests are in the area of hybrid optical fiber-wireless communication systems.



Xianbin Yu received a PhD from Zhejiang University, Hangzhou, China, in 2005. From October 2005 to October 2007, he was a postdoctoral researcher with Tsinghua University, Beijing, China. In November 2007, he became a postdoctoral research fellow with DTU Fotonik, Technical University of Denmark, Lyngby, Denmark, where he is currently an assistant professor. He co-authored one book chapter and over 60 peer-reviewed international journal and conference papers. His research interests are in the areas of microwave photonics, optical-fiber communications, wireless-over-fiber, ultrafast photonic wireless signal processing, and ultrahigh-speed short-range access technologies.



Ying Zhao was born in Beijing, China, in 1984. He received a BS in electronic engineering from Peking University, Beijing, China, in 2007. He is currently working toward a PhD at the Department of Electronic Engineering, Tsinghua University and he is also a guest PhD student of the Department of Photonics Engineering, Technical University of Denmark. His current areas of interest are high-speed optical communications and radio-over-fiber technology.



Lei Deng received BS and MS degrees in optoelectronics and information engineering from Huazhong University of Science and Technology, Wuhan, China, in 2006 and 2008, respectively. He is a PhD candidate at the same university. Now he is in the Technical University of Denmark as a guest PhD student. His research interests include fiber-optic communications, advanced modulation formats, and OFDM in radio-over-fiber (RoF) systems and next-generation passive optical

network (PON) systems.



Darko Zibar received the MSc degree in telecommunication in 2004 from the Technical University of Denmark and the PhD degree in 2007 from the Department of Communications, Optics and Materials, COM_DTU within the field of optical communications. He was a visiting researcher with Optoelectronic Research Group at the University of California, Santa Barbara (UCSB) from January 2006 to August 2006. From February 2009 until July 2009, he was visiting researcher

with Nokia-Siemens Networks. Currently, he is employed at DTU Fotonik, Technical University of Denmark as the assistant professor. His research interests are in the area of coherent optical

communication, with the emphasis on digital demodulation and compensation techniques. He is a recipient of the Best Student Paper Award at the IEEE Microwave Photonics Conference (MWP) 2006 as well as Villum Kann Rasmussen postdoctoral research grant in 2007.



Idelfonso Tafur Monroy is currently professor and head of the metro-access and short range communications group of DTU Fotonik at the Technical University of Denmark. He received a MSc degree from the Bonch-Bruевич Institute of Communications, St. Petersburg, Russia, in 1992. He received a Technology Licenciante degree from the Royal Institute of Technology, Stockholm, Sweden, in 1996. In 1999 he received a PhD degree from the Electrical Engineering

Department of the Eindhoven University of Technology, the Netherlands and worked as an assistant professor until 2006. He is currently involved in the ICT European projects GiGaWaM and EURO-FOS and is the technical coordinator of the ICT-CHRON project. His research interests are in hybrid optical-wireless communication systems, high-capacity optical fiber communications, digital signal processing for baseband, and radio-over-fiber links, application of nanophotonic technologies in the metropolitan and access segments of optical networks as well as in short-range optical-wireless communication links.