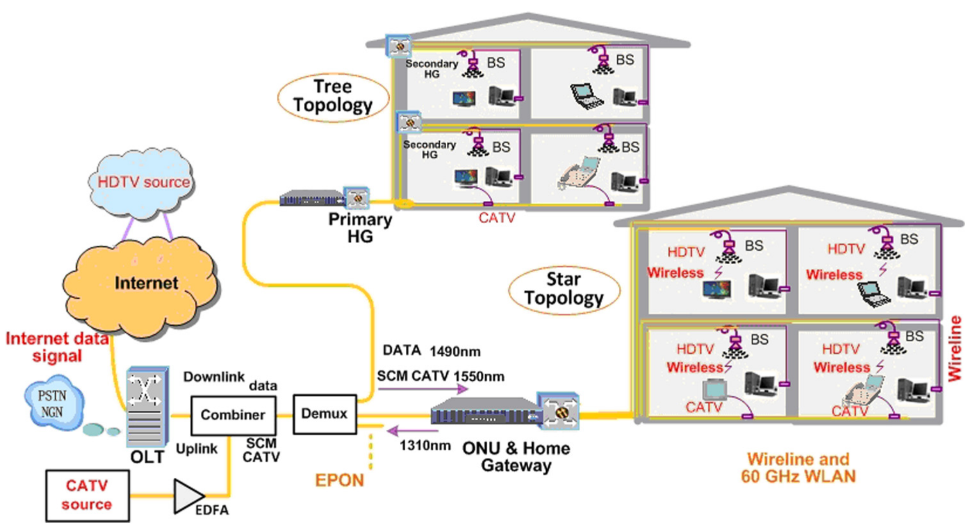
IEEE Photonics Journal
An IEEE Photonics Society Publication

Invited Paper

Enabling ROF Technologies and Integration Architectures for In-Building Optical–Wireless Access Networks

Volume 2, Number 2, April 2010

Kun Xu
Xiaoqiang Sun
Jie Yin
Hao Huang
Jian Wu
Xiaobin Hong
Jintong Lin



DOI: 10.1109/JPHOT.2010.2043665
1943-0655/$26.00 ©2010 IEEE

Enabling ROF Technologies and Integration Architectures for In-Building Optical–Wireless Access Networks

Kun Xu, Xiaoqiang Sun, Jie Yin, Hao Huang, Jian Wu, Xiaobin Hong, and Jintong Lin

(Invited Paper)

Key Laboratory of Information Photonics and Optical Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China

DOI: 10.1109/JPHOT.2010.2043665
1943-0655/$26.00 ©2010 IEEE

Manuscript received January 7, 2010; revised February 11, 2010. First published Online February 19, 2010. Current version published March 5, 2010. This work was supported by the National 863 Program of China under Grant 2007AA01Z264, the National Natural Science Foundation of China under Grant 60702006, Grant 60736002, Grant 60837004, and Grant 60932004, the New Century Excellent Talents under Grant 06-0093, the Program for Changjiang Scholars and Innovative Research Team in University under Grant IRT0609, the Ministry of Science and Technology International Cooperation Program under Grant 2008DFA11670, the 111 Project under Grant B07005, and the project funded by the State Key Laboratory of Advanced Optical Communication Systems and Networks, China. Corresponding author: K. Xu (e-mail: xukun@bupt.edu.cn).

Abstract: This work presents our recent progress on advanced radio-over-fiber (ROF) technologies for in-building optical–wireless access networks, including multiservice, full-duplex, and polarization diversity ROF system design, as well as the experimental delivery of uncompressed high-definition television (HDTV) signals. The novel polarization diversity technique is proposed to improve receiving sensitivity and increase the anti-interference capacity of the wireless transmission at the in-building environment. Furthermore, the integration architecture of ROF and Ethernet passive optical network (EPON) is investigated, mainly focusing on polar duplex antenna for non-line-of-sight (NLOS) transmission and home gateway for different network topologies. The hybrid system distributes the multimedia services (e.g., HDTV in EPON) and other wireless data services to the terminal rooms over ROF links and thus expands the superbroadband EPON services to the subscribers for the last meters in both wired and wireless ways.

Index Terms: Optical–wireless, in-building network, radio-over-fiber (ROF), Ethernet passive optical network (EPON), home gateway.

1. Introduction

Personal home network has experienced an unprecedented development in recent years, since the advent of personal computers (PCs), video phones, and high-definition television (HDTV), as well as the high demand of security surveillance and remote medical monitoring. The continuing remarkable growth in the traffic of multimedia services should also meet the requirement of in-building wired and wireless services convergence to offer customers with greater choice, convenience, and variety in an efficient way, anywhere and anytime. In addition to the personal areas, some hot spots, such as conference centers, airports, hotels, and shopping malls, also have broadband multimedia services demands both in wired and wireless access [1]. Consequently, this requirement has promoted the development of both wired and wireless access technologies. On one hand, the wavelength-division-multiplexed passive optical network (WDM PON) has long been considered as an ultimate solution for the broadband wired access network capable of providing > 10-Gb/s data to each subscriber [2]. On the other hand, 60-GHz millimeter wave (MMW) is of special interest for local wireless multimedia access, due to the high atmosphere attenuation, close to 15 dB/km, and this band communications own the advantages of anti-interference ability, high security and high bandwidth. Furthermore, the Federal Communications Commission (FCC) has already allocated an unprecedented 7 GHz of continuous spectrum for license free operation between 57–64 GHz, which is the largest contiguous block of radio spectrum ever allocated [3]. Therefore, the 60-GHz band is the most promising solution to multi-gigabit-per-second wireless access for in-building applications, such as HDTV and other multimedia services [2]. Nevertheless, it also has several technical obstacles to overcome and reduces the cost for practical applications. High atmospheric attenuation in this block of radio spectrum results in a small coverage radius for the base station (BS), and thus lots of BSs with full-duplex system would be necessary to cover one specific area, and this requires a BS with low cost and flexible management in order to make it cost-effective and practical. In this case, in order to utilize the huge bandwidth of the fixed access network and provide both wired and wireless services to the subscribers, radio-over-fiber (ROF) technology becomes the powerful choice for the superbroadband optical–wireless access for in-building networks [4]. Numerous efforts have been dedicated to ROF system design and demonstration, including full-duplex multiservice ROF system [5]–[8], photonic vector modulation [9], [10], and digital radio frequency over fiber technology [11].

In this paper, we have a brief introduction to our recent investigation on a cost-effective architecture of the in-building optical–wireless access network for wired and wireless multimedia services using ROF technology at first. Next, we summarize our previous progress on advanced ROF systems design and demonstration. The corresponding work includes multiservice, full-duplex, and polarization diversity ROF systems design, as well as the experimental delivery of uncompressed HDTV signals. In addition, some important issues for 60-GHz wireless multimedia access over fiber are discussed in the last section, including polar duplex antennas for non-line-of-sight (NLOS) transmission and home gateway (HG) architectures for different network topology. In order to make this architecture more available and cost-effective, we utilize the unified passive optical network (PON) facilities and equipments to provide the multiservice to the HG and use ROF links to distribute the upconverted wireless signals to each terminal room. For practical application, ROF technologies can only provide the solution to wireless signal frequency upconversion and distribution over fiber, while there are also many issues deserve the further research, such as NLOS transmission of 60-GHz wireless signal at indoor environment and control layer for integration of PON and ROF links. For the latter issue, we only introduce some further investigation at present. This paper is organized as follows. The in-building wired and wireless network architecture for multiservice providing is presented in Section 2. We summarize the results of our recent works in physical layer, including multiservice, full-duplex, polarization diversity ROF system design, and demonstration of delivery of uncompressed HDTV signals, in Section 3. Polar duplex antennas for NLOS transmission and HG architectures for different network topology are briefly described in Section 4.

2. In-Building Wired and Wireless Network Architecture for Multiservice Providing

Fig. 1 illustrates the generic system architecture based on ROF technologies and EPON network for providing multiservice in in-building optical–wireless networks. In order to meet the requirement of network integration among telecommunications, television and Internet, the unified optical network facilities and equipments are used to share the network resources, which reduces the operating and maintenance costs, and provides future ultrahigh-definition TV, stereo television, interactive multimedia games, and other broadband services both in wired and wireless way at indoor environment. In Fig. 1, optical network unit (ONU) and HG are combined to realize the traffic providing, frequency upconversion, and the resources control. The system distributes the multimedia services (e.g., HDTV in EPON) and other wireless data services to the terminal

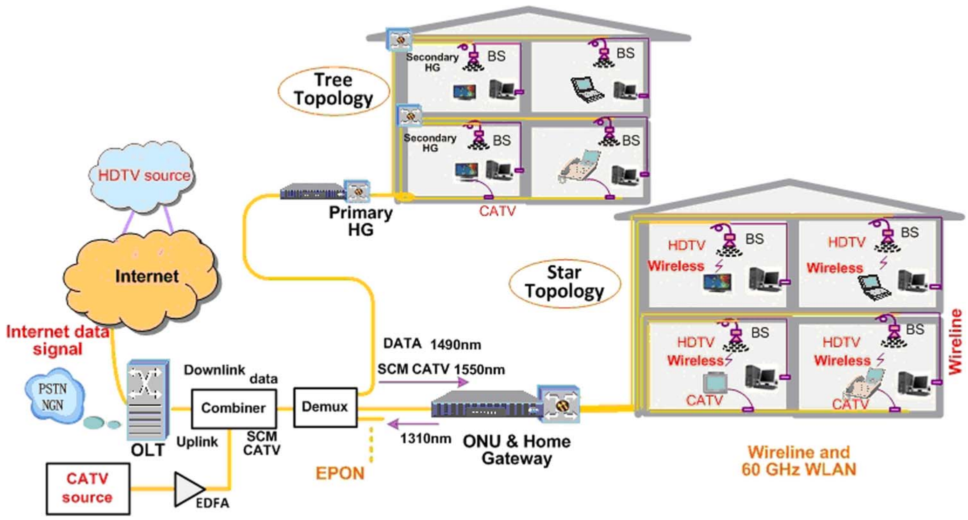


Fig. 1. System architecture based on ROF technologies and EPON network for providing multiservice in in-building optical–wireless networks.

rooms over ROF links, expands the EPON services to the subscribers for the last meters, and realizes the uplink transmission, in both wired and wireless way. Actually, the network topology is different according to the number of the subscribers. The star topology is more attracting for small amount of users, while tree topology is suitable for large amount of users. Therefore, the corresponding structures of HG are designed for different topologies. In tree network topology, the second-level gateway is used to distribute and combine the traffic. Our proposed structure is quiet different from that in reference [5], which mainly focuses on the physically distribution of 60-GHz-band MMW services as well as 2.4-GHz WiFi and 5.8-GHz WiMax signals, while in our work, we dedicate to the integration of home wired and wireless network with the external Internet, and there is no alteration of the existing PON facilities. And more issues for the practical application is considered, including full-duplex, polarization diversity ROF system, polar duplex antennas for NLOS transmission and HG architectures for different network topology. It should be clarified that the presentation of the overall convergent network has not covered all the corresponding interesting technologies, some of which have not been accomplished at present.

3. Enabling ROF Technologies and Experiment Demonstration

3.1. Multiservice ROF System

We proposed a simple scheme to generate and distribute hybrid wireless services. The 34.8-GHz MMW and 11.6-GHz microwave (MW) are optically generated simultaneously through a single Mach–Zehnder modulator (MZM) and a comb filter, with a MW source of only 5.8 GHz. The obtained MMW are successfully transmitted in the air with a data rate of 1.25 Gb/s. The experiment setup is shown in Fig. 2. At the central office (CO), the 1545.5-nm light from a laser diode is upconverted by a MZM with a 3-dB bandwidth of 10 GHz. The MZM is biased at V_π (about 3.6 V) to suppress all even sidebands. The electrical drive signal generated by MW source with a frequency of 5.8 GHz, is boosted to 26 dBm by an electrical amplifier (EA) before driving the MZM. A 25-GHz/50-GHz interleaver is adopted to separate the first-order and the third-order sidebands, so the optical MW and MMW signals with double and sextuple frequency of drive signal are obtained, which are 11.6 GHz and 34.8 GHz, respectively. Then they are used to carry data1 (622 Mb/s) and data2 (1.25 Gb/s), respectively. These two branches are amplified by EDFA and transmitted in 25-km single-mode fiber (SMF). After the photodetector (PD), MW signal is boosted by EA and

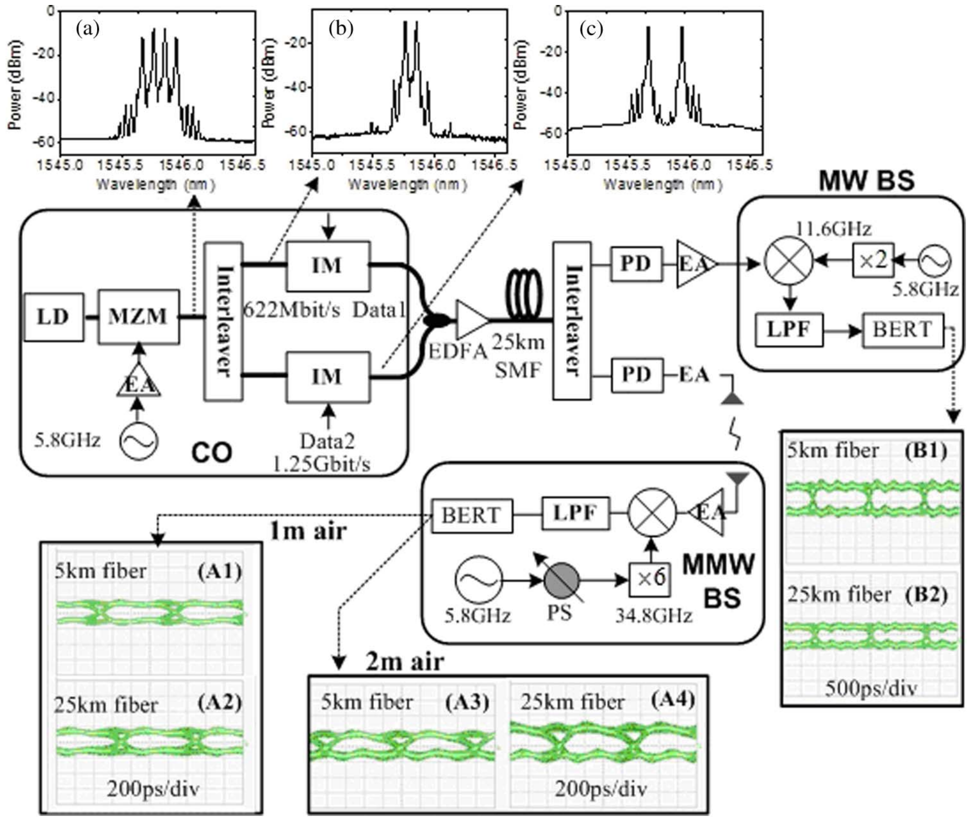


Fig. 2. Experimental setup and results of the multiservice ROF system. Inset (a)–(c) Measured optical spectra at the positions as indicated in the diagram. (A1)–(A4) Measured eye diagram of wireless downlink transmission. (B1)–(B2) Eye diagram of back-to-back transmission.

then input to the electrical mixer. An electrical frequency doubler is used to generate 11.6-GHz local oscillator. The eye diagram of data1 after demodulation is shown in Fig. 2 (B1)–(B2).

The MMW signal is obtained through O/E conversion of a PD with a 3-dB bandwidth of 70 GHz and then amplified by EA. A pair of MMW antenna with a frequency range of 26.5–40 GHz and a gain of 15 dBi is used to send and receive the MMW signals. The distance of wireless transmission is two meters. The eye diagram of data2 after demodulation is shown in Fig. 2 (A1)–(A4). We demonstrated the MMW wireless transmission for 1 m and 2 m in the air, respectively in the condition of 5-km and 25-km SMF, and also demonstrated the MW transmission in 5-km and 25-km SMF. The eye diagrams of demodulated data1 and data2 are inset in Fig. 2.

3.2. MMW PSK Modulation and Full-Duplex ROF System

Full-duplex operation is necessary in practical ROF applications, and the wavelength reuse technique is highly desirable to reduce the cost. We proposed a scheme of full-duplex operation based on an FBG with a reflectivity of 50%. Both downlink and uplink transmissions are experimentally demonstrated. In addition, phase-shift keying (PSK) modulation has many advantages over intensity modulation in wireless transmission [6]. In this paper, we also proposed a method in which we made the two sidebands of MMW pass through the electric-optic phase modulator (PM) with opposite direction to generate MMW with PSK format. Furthermore, the generated PSK signals can be demodulated as simply as ASK and no special component is needed.

The experimental setup and measured results are shown in Fig. 3(a). A tunable laser is used to generate the continuous wave with 4-dBm power initially. A zero-chirp MZM biased at minimum point

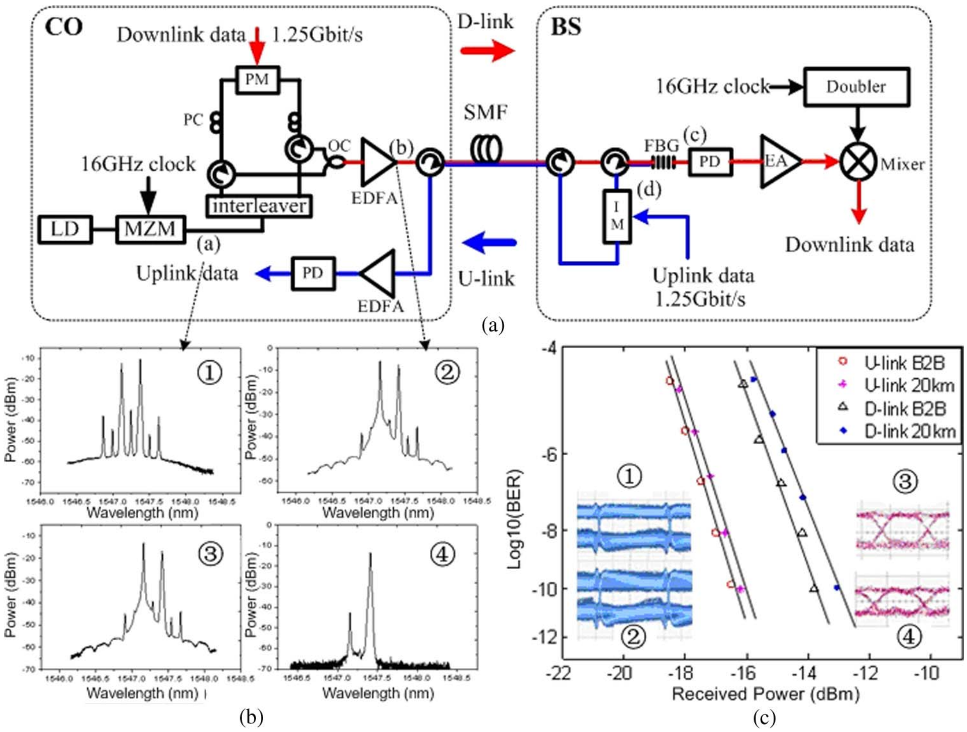


Fig. 3. Experimental setup of the PSK modulation and full-duplex operation. (a) Experimental setup. (b) Optical spectrum of each point in experimental setup. (c) BER plot curves of downlink and uplink transmissions.

is driven by a 16-GHz clock by optical carrier suppression modulation. The generated upper and lower sidebands are separated by a 25/50-GHz interleaver. Then they pass through the electro-optic PM in opposite direction. The downlink data (1.25-Gb/s PRBS with a word length of $2^{13}-1$) is loaded on the two sidebands through the PM. These two sidebands are separated by two circulators and combined again by a 3-dB optical coupler. Then the optical MMW signal with PSK modulation is obtained. At the BS, the received optical signal is filtered out by a FBG before photodetection. The reflectivity of the FBG at the central wavelength is about 50%, and the reflective bandwidth is less than 0.2 nm. The transmitted light after the FBG is detected and demodulated. Meanwhile, the reflective light of the FBG is used as the carrier for the uplink transmission. Thus the full-duplex operation can be realized with the wavelength reuse technique.

In Fig. 3(b), insets ① and ② indicate the measured optical spectrum after the MZM and the loop comprised by a PM. The reflective spectrum and the transmission spectrum is shown in insets ③ and ④, from which we can observe that the reflective light mainly includes the idle sideband, another sideband contains the downlink data is suppressed to nearly 30 dB lower than the idle sideband. The transmitted light spectrum does not change much except the power of idle sideband decreases nearly 3 dB. The transmitted light after the FBG is O/E converted by a PD with a 3-dB bandwidth of 70 GHz and amplified by an MMW EA. An electrical mixer is used to demodulate the downlink data. The 32-GHz local oscillator is provided by a 16-GHz MW source and a doubler. The reflective light of the FBG is used as the carrier of the uplink transmission. An MZM with a low insertion loss of about 3 dB is employed to load the uplink data (1.25-Gb/s PRBS). The uplink light can multiplex with the downlink light in the same fiber link by two circulators. The BER curves of uplink and downlink transmissions are measured and shown in Fig. 3(c). The power penalty of the 20-km SMF transmission of downlink and uplink without dispersion compensation are about 0.8 dB and 0.2 dB, respectively. The demodulated eye diagrams for B-T-B and 20-km SMF transmission are also inset in Fig. 3(c).

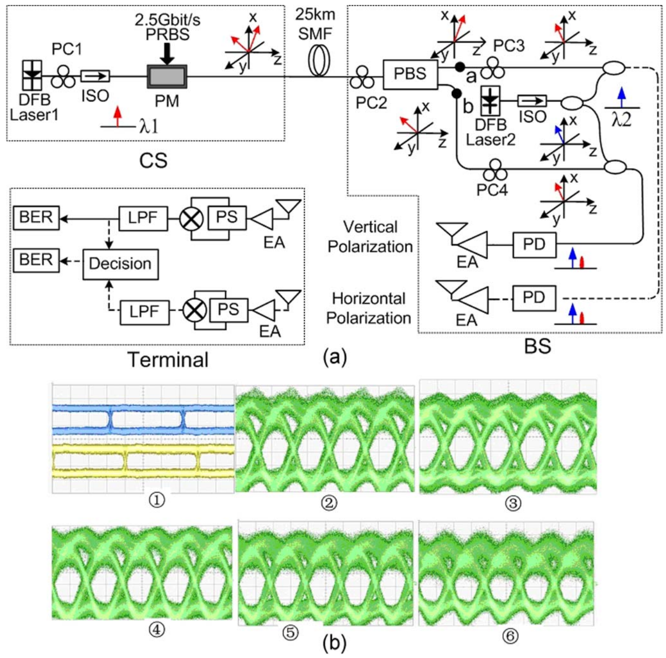


Fig. 4. Experimental setup and results of the polarization diversity ROF system. (a) Experimental setup. (b) Eye diagram of the demodulated 2.5-Gb/s signal. Inset ① Signals at plot a and plot b; ② signals after 25-km SMF and 24-cm wireless transmission without EA; ③, ④, ⑤ signals after 25-km SMF and 52-cm, 1.6-m, 4-m wireless transmission, respectively with EA, ⑥ BTB signal after 4.4-m wireless transmission with EA.

3.3. Polarization Diversity ROF System

Polarization diversity, early applied to high-frequency radar, and imaging systems, has demonstrated its potential for improving the capacity of wireless communications systems [12]. In this paper, we proposed a novel ROF scheme to obtain polarization diversity for the first time to our knowledge [7]. This technique is helpful to improve receiving sensitivity and increase the anti-interference capacity at the in-building wireless environment.

The basic principle of the proposed approach is based on the modulation characteristics of electro-optic PM and high sensitivity of heterodyne detection. As illustrated in Fig. 4(a), the central station (CS) consists of a PM and a DFB laser. The CW light is generated at $\lambda 1 = 1545.602$ nm. The 2.5-Gb/s PRBS baseband data is injected into the PM and the data is modulated onto the carrier with two orthogonal polarizations. After transmission of a 25-km SMF, the optical signal is split into two branches and converted to ASK signals after the polarization beam splitter (PBS). Each branch of optical signal is adjusted by a polarization controller (PC) to obtain the same polarization with the coherent light generated by another DFB laser with initially power of 13.2 dBm at 1545.482 nm. At the terminal, the RF signal received by one antenna with horizontal or vertical polarization is separated into two paths by a power splitter after amplifying by an EA. Then, one path of RF signal is multiplied with the other and the original 2.5-Gb/s signal is recovered. The impact of minor wavelength spacing drift between two lasers can be decreased in this polarization diversity structure, because the signals of the upper and lower emitting antennas have the same frequency drift. When two signals with opposite direction are recovered, one better signal or the processing result of the two signals can be obtained and wireless polarization diversity is realized and receiving sensitivity can be improved.

For the high power of the LO light, the RF power of the PD can reach 3 dBm and the transmission of 24-cm wireless distance through two 20-dBi horn antennas without any EA is realized, and the eye diagram is illustrated in Fig. 4(b) inset ②. Inset ① in Fig. 4(b) shows the eye diagrams of the received signals at the nods *a* and *b* indicated in Fig. 4(a). To extend the transmission length, one

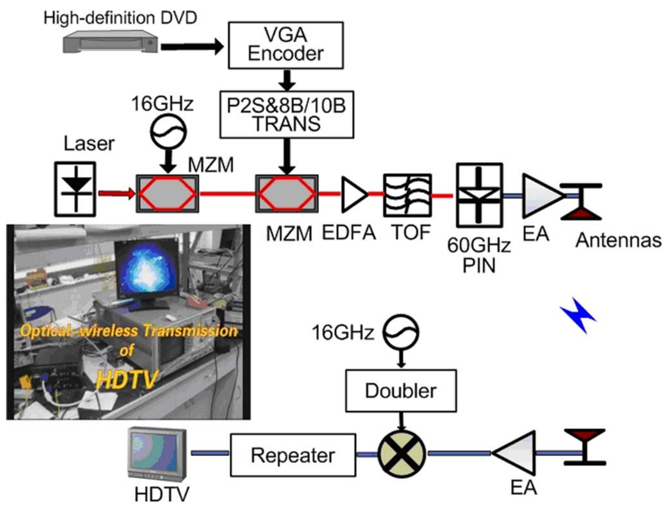


Fig. 5. Experimental setup and partly demonstration platform of the uncompressed HDTV signal transmission.

25-dB RF EA with a bandwidth of 10 GHz centered at 15 GHz is used to amplify the electrical signal. The eye diagrams at wireless distances of 0.52 m, 0.24 m, 1.6 m, 4 m, and 4.4 m are shown in Fig. 4(b) insets ②–⑥, respectively. When the distance is 0.52 m, the sensitivity can be as low as −32 dBm, which has not been reported in previous experiment. The receiver sensitivity deteriorates quickly as the wireless distance increases due to the power loss and indoor multipath distortion, as shown in Fig. 4(b). The noise of inset ⑥ in Fig. 4 is larger than that of insets ②–⑤, due to the reflection and deflection in the indoor environment.

In conclusion, a novel scheme of optically generated 2.5-Gb/s PSK signals and the wireless transmission of respective ASK signals with 15-GHz electrical carrier based on heterodyne detection is experimentally demonstrated, and this can realize the wireless polarization diversity and simplify the structure of the wireless BS largely.

3.4. HDTV Demonstration Platform

Based on the previous work and the proposed ROF systems, we realized a 32-GHz MMW over fiber system loading 1.3-Gb/s uncompressed HDTV service by upconversion technique. Both the cost and complexity of the video display equipment (e.g., HDTV) can be decreased, as there is no need to use a transcode to convert a compressed HD video format into another compression format. The experimental setup and partly demonstration platform of the uncompressed HDTV signal transmission is illustrated in Fig. 5. The 16-GHz clock is modulated onto the optical by optical-carrier-suppressed (OCS) modulation, and the uncompressed HDTV signals from the DVD player are encoded and transformed before injecting into the MZM. After photodetection and wireless transmission, the signals are demodulated and displayed by the HDTV. In this experimental demonstration, the MMW band antennas and other components are the same as the experiment in Section 3.3 [7], but signal modulation and frequency upconversion employ the simplest method which are intensity modulation and OCS modulation. And we monitor the transmission quality only by the display quality of the HDTV, without the record of BER and eye-diagram results. When the distance between the transmitting and receiving antennas is 5 m, the obtained video quality is quiet smooth, and it deteriorates if the distance is increased or obstacle like hand is put between the two antennas. The 32-GHz MMW ROF transmission demonstration of HDTV signals also provides a new chance of multi-gigabit-per-second transmission for many consumer electronics applications for its simplicity and huge bandwidth. This demonstration indicates that the optical–wireless system based on ROF technology can distribute the superband multimedia services for in-building network. It should be clarify that, although the HDTV

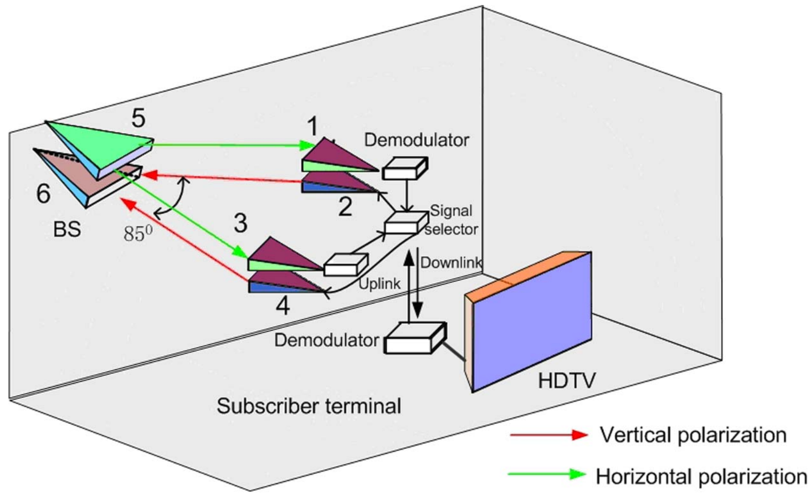


Fig. 6. Polar duplex antennas for NLOS transmission.

demonstration has not bring any new idea to ROF technology for high-data-rate transmission, this can be the basic platform for HDTV and other multimedia services transmission, and the subcarrier frequency can be extended to much higher, and the encoding as well as transforming of the signals from DVD player is also important for future more multimedia service demonstration.

4. Further Investigations in 60-GHz Wireless Multimedia Access

The 60-GHz MMW band is of much interest since a continuous spectral space (7 GHz) has been allocated worldwide for dense wireless local communications, and it can provide the promising solution to multi-gigabit per-second wireless access with anti-interference ability, high security and high bandwidth. Unfortunately, the 60-GHz wireless channel shows 20–40-dB increased free-space path loss and suffers from 15- up to 30-dB/km atmospheric absorption, depending on the atmospheric conditions [13]. In principle this higher free-space loss can be compensated for by the use of antennas with more pattern directivity while maintaining small antenna dimensions. When such antennas are used, however, antenna obstruction (e.g., by a human body) and mispointing may easily cause a substantial drop of received power, and this makes NLOS communication very difficult at 60 GHz [14].

Another technical challenge is the network integration between ROF links and the existing PON. The exploitation of the ROF technologies including frequency upconversion and wavelength reuse in optical access network is not straightforward. Actually, the present efforts are most dedicated to the physical links for wireless signals distribution over the fiber. For in-building optical–wireless network, the integration of EPON and ROF technology and the HG architecture has been further investigated in our work. In this section, we will briefly present the polar duplex antenna to make NLOS transmission of MMW possible, and give the architectures of the gateway for different network topology.

4.1. Polar Duplex Antenna for NLOS Transmission

As the 60-GHz MMW band suffers from high attenuation due to the atmospheric oxygen absorption, broadband MMW communication around 60 GHz has high security and low interference. However, there are some technical obstacles to overcome for practical applications, the difficulties including frequency reuse, line-of-sight (LOS) transmission blocking and electromagnetic radiation power control. In our work, we use space multiplexing to achieve frequency reuse. As shown in Fig. 6, two fan-shaped antennas at the BS are installed on the wall at different height to obtain enough isolation, and the transmitter (antenna 5) and the receiver (antenna 6) can utilize the same

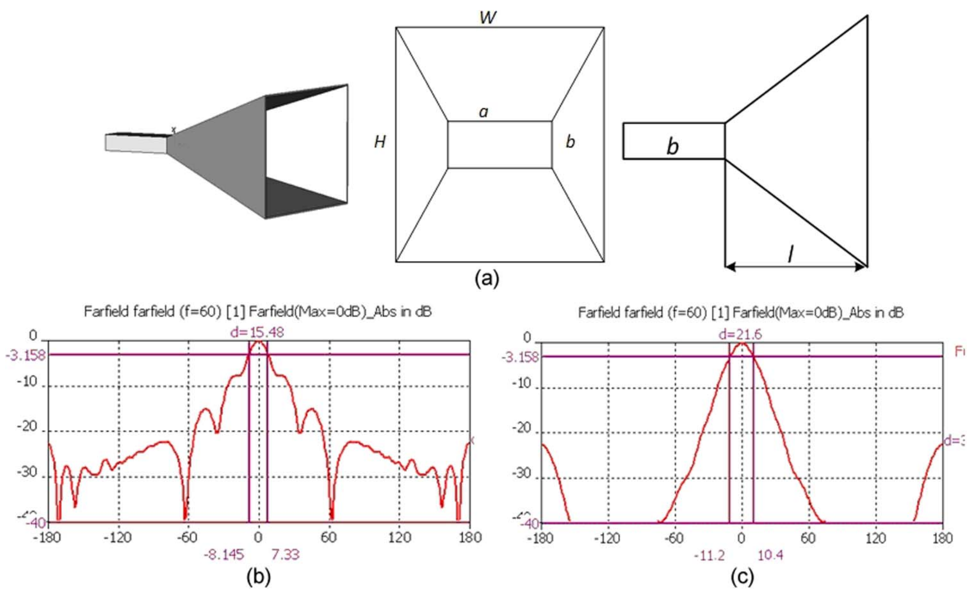


Fig. 7. Antenna models and simulation directional patterns. (a) Shape and size of the horn antenna. (b) Directional pattern in E plane. (c) Directional pattern in H plane.

bandwidth. Thus, the frequency reuse can be obtained and the terminal structure can be simplified. In the client antennas, antenna 1, 2 and antenna 3, 4 are also employed in the space multiplexing way. To solve the transmission blocking problem, fan-shaped antennas are installed in a special way. The wide directional antenna 5, 6 are installed at the corner of the house and can cover the whole room. Two pairs of narrow directional antennas (antenna 1, 2 and antenna 3, 4) are installed at different places near the HDTV set. There are two ways to process multiple receiving antennas signals in order to get the high-quality signals. One method is to select stronger signal among the two receiving antennas as the final result and this method is simple and easy to implement, but the signal quality is not high. The other method is to use multichannel signal equalization, and it can improve the signal performance while the equalization algorithm is complex and requires high-speed digital signal processing module.

The client antennas (antennas 1–4 in Fig. 6) are two pairs of narrow-beam and high-gain antennas. These four antennas are designed as the horn-shaped antennas with the high gain of 20 dB. In the multiplexing way, the antennas 1, 3, 5 are worked in horizontal polarization, while antenna 2, 4, 6 are in vertical polarization, thus we can obtain extra isolation between two nearby antennas such as antenna 5 and antenna 6. The shape of the antenna is shown in Fig. 7(a). We use BJ620 waveguide feed antennas, and the parameters are also given in Fig. 7(a), where $a \times b = 3.759$ mm $\times$ 1.88 mm, $W \times H = 24.45$ mm $\times$ 16.6 mm, and $l = 21.17$ mm. The simulated directional patterns are shown in Fig. 7(b), and the simulated antenna gain is 19.3 dB.

4.2. Architecture Design of the HG

In the in-building optical–wireless network, the HG is one of the most essential devices for implementing the intelligent ubiquitous services. It connects the access network, wide area network (WAN), to the home network, and then enables the transmission and reception of all packet traffic between indoor devices and outdoor systems [15]. The demand of household bandwidth-hungry applications results in the providing of high-bandwidth services like HDTV, CATV, and Ethernet concurrently. In this paper, intelligent optical–wireless residential gateway is proposed as a feasible and advanced solution to combine PON and ROF links, which is a more efficient, flexible, and also a future-prone architecture to be employed in the last-mile scenario. Two network architectures and corresponding RG structures are designed for delivering in-building multimedia services, whose

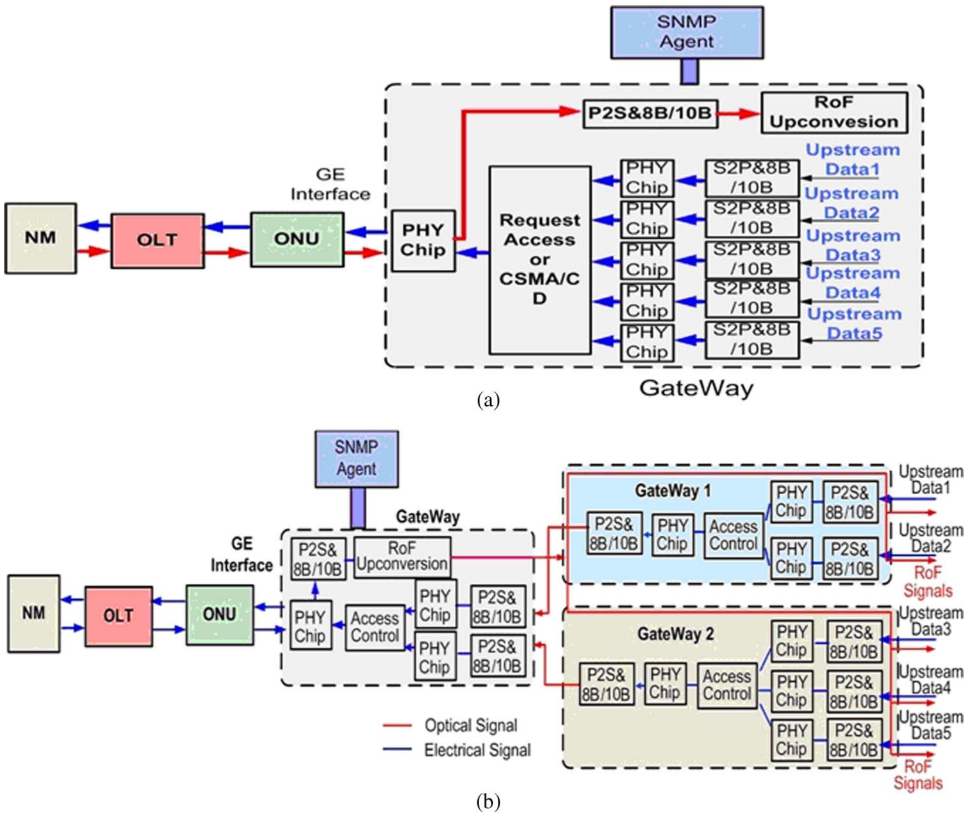


Fig. 8. Structural diagram of the HG for different network topology. (a) Star topology. (b) Tree topology.

transportation features are controlled by embedded network manage systems and dynamic bandwidth allocation algorithms.

In practical application, the network topology is different according to the number of the subscribers. The star topology is more attracting for small amount of users, while tree topology is suitable for a large number of users. The star topology diagram of the HG is shown in Fig. 8(a). The downlink signals are distributed to the subscribers through only one upconversion module in order to simplify the structure and reduce the overall costs, as the BS do not need the expensive 60-GHz local oscillator and MMW band mixer. The upstream data would be aggregated at the gateway and sent to the ONU. In order to reduce the overall cost, we employ direct modulation in the uplink data transmission. At the BS, the uplink 60-GHz signals are downconverted only by square-law detection. Hence, the MMW band signal received from antenna are downconverted to the baseband with LO free and high-frequency mixer free. Then, the baseband data is modulated with the optical transceiver directly. This eliminates requirement of high-frequency optical modulator and high-frequency MMW mixer at the BS. The tree topology structural is shown in Fig. 8(b), and the structure is divided into several levels in order to satisfy large amount of users. The upconversion and downconversion of the 60-GHz signals have the same principle as the aforementioned. To sum up, the proposed HG for different network topology can play a key role in the integration of the ROF links and the EPON network.

5. Conclusion

We present our recent progress on advanced ROF technologies for in-building optical–wireless access networks. The key technologies, including multiservice ROF system, MMW PSK modulation and full-duplex ROF system, polarization diversity ROF systems design, and experimental delivery of uncompressed HDTV signals are focused on. It is noted that the novel polarization diversity technique can be used to improve receiving sensitivity and increase anti-interference capacity of the wireless transmission at the in-building environment. Furthermore, the integration architecture of ROF and EPON is investigated, mainly focusing on polar duplex antenna and HG for different network topology. The hybrid system distributes the multimedia services (e.g., HDTV in EPON) and other wireless data services to the terminal rooms over ROF links and thus expands the superbroadband EPON services to the subscribers for the last meters in both wired and wireless way.

References

[1] M. Huchard, M. Weiss, A. Pizzinat, S. Meyer, P. Guignard, and B. Charbonnier, "Ultra-broadband wireless home network based on 60-GHz WPAN cells interconnected via RoF," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2364–2372, Aug. 2008.

[2] K. Y. Cho, Y. Takushima, and Y. C. Chung, "10-Gb/s operation of RSOA for WDM PON," *IEEE Photon. Technol. Lett.*, vol. 20, no. 18, pp. 1533–1535, Sep. 2008.

[3] P. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: Prospects and future directions," *IEEE Commun. Mag.*, vol. 40, no. 1, pp. 140–147, Jan. 2002.

[4] J. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.

[5] A. Chowdhury, H. Chien, Y. Hsueh, and G. K. Chang, "Advanced system technologies and field demonstration for in-building optical-wireless network with integrated broadband services," *J. Lightw. Technol.*, vol. 27, no. 12, pp. 1920–1927, Jun. 2009.

[6] H. Huang, K. Xu, Y. Zhang, F. Tang, R. Zhu, X. Hong, J. Wu, and J. Lin, "A novel scheme for mm-wave PSK modulation and full-duplex operation in ROF system," in *Proc. Int. Top. Meeting MWP/APMP*, Gold Coast, Australia, Oct. 2008, pp. 162–164.

[7] J. Yin, K. Xu, Y. Li, X. Sun, L. Gui, J. Wu, X. Hong, and J. Lin, "Demonstration of 2.5 Gb/s optical PSK signal and the ASK wireless transmission based on heterodyne detection in a radio-over-fiber platform," in *Proc. Int. Top. Meeting MWP*, Valencia, Spain, Oct. 2009, pp. 1–3.

[8] J. Yin, K. Xu, Y. Li, J. Wu, X. Hong, and J. Lin, "Demonstration for delivering of optical DPSK signal in a ROF platform based on heterodyne detection," in *Proc. OFC, JWA50*, San Diego, CA, Mar. 2009, pp. 1–3.

[9] Y. Zhang, K. Xu, R. Zhu, H. Huang, J. Wu, X. Hong, and J. Lin, "Photonic DPASK/QAM signal generation at microwave/millimeter-wave band based on electro-optic phase modulator," *Opt. Lett.*, vol. 33, no. 19, pp. 2332–2334, Oct. 2008.

[10] X. Sun, K. Xu, S. Fu, J. Li, X. Hong, J. Wu, J. Lin, and P. Shum, "All-optical WDM subcarrier modulator for BPSK with optical SSB format using a phase modulator loop mirror filter," in *Proc. OFC, JWA56*, San Diego, CA, Mar. 2009, pp. 1–3.

[11] A. Nirmalathas, C. Lim, D. Novak, P. Gamage, R. Waterhouse, and Y. Yang, "Digitized RF transmission over fiber," *IEEE Microw. Mag.*, vol. 10, no. 4, pp. 75–81, Jun. 2009.

[12] J. F. Valenzuela-Valdés, M. A. García-Fernández, A. M. Martínez-González, and D. Sánchez-Hernández, "The role of polarization diversity for MIMO systems under Rayleigh-fading environments," *IEEE Antennas Wireless Propag. Lett.*, vol. 5, no. 1, pp. 534–536, Dec. 2006.

[13] C. Anderson and T. Rappaport, "In-building wideband partition loss measurements at 2.5 and 60 GHz," *IEEE Trans. Wireless Commun.*, vol. 3, no. 3, pp. 922–928, May 2004.

[14] R. C. Daniels and R. W. Heath, "60 GHz wireless communications: Emerging requirements and design recommendations," *IEEE Veh. Technol. Mag.*, vol. 2, no. 3, pp. 41–50, Sep. 2007.

[15] W. Park and D. Kim, "Convergence of broadcasting and communication in home network using an EPON-based home gateway and overlay," *IEEE Trans. Consum. Electron.*, vol. 51, no. 2, pp. 485–493, May 2005.