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Utilizing Single Lightwave for Delivering Baseband/FSO/MMW Traffics Simultaneously in PON Architecture

CHIEN-HUNG YEH[1], WEN-PIAO LIN[2,3], CHIEN-MING LUO[1], YUE-RU XIE[1], YAO-JEN CHANG[1], AND CHI-WAI CHOW[4]

[1]Department of Photonics, Feng Chia University, Taichung 40724, Taiwan
[2]Department of Electrical Engineering, Chang Gung University, Taoyuan 33302, Taiwan
[3]Department of Holistic Medicine, Linkou Chang Gung Memorial Hospital, Taoyuan 33302, Taiwan
[4]Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

Corresponding authors: Chien-Hung Yeh (yeh1974@gmail.com) and Wen-Piao Lin (wplin@mail.cgu.edu.tw)

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ABSTRACT In this work, we demonstrate an integrated optical baseband, free space optical (FSO) communication and millimeter-wave (MMW) traffics through the present passive optical network (PON) architecture by utilizing single wavelength for broadcasting triple-play services. In the execution, we exploit 10 Gbit/s on-off keying (OOK) modulation on 10 GHz Mach-Zehnder modulator (MZM) to produce the downstream baseband signal. And the 10 Gbit/s baseband signal also can cause FSO traffic within the forward error correction (FEC) target after 25 km fiber and 160 m free space transmissions. Moreover, we can utilize the fiber to the extension (FTTE) scheme to provide the 36.42 GHz MMW with 10 Gbit/s OOK data after 25 km fiber link and 8 km extended fiber transmission.

INDEX TERMS Optical wireless communication (OWC), passive optical network (PON), millimeter-wave (MMW), free space optical (FSO).

I. INTRODUCTION

Due to the emergence of various broadband multi-service gradually, such as cloud access, artificial intelligence (AI) application, IP-based traffic, 4K/8K video, on-line game and social networking, the utilization of widely bandwidth is also increase in the access network [1], [2]. Hence, to meet with the broadband requirement for the end-user, the time-division-multiplexing (TDM), wavelength-division-multiplexing (WDM) and time- and wavelength-division-multiplexing (TWDM) passive optical network (PON) access techniques have been investigated and deployed worldwide [3]–[5]. The development trend of PON networks have been proposed and investigated from 2.5 to 100 Gbit/s for baseband downstream. However, some locations are not suitable to build the fiber connection due to the restrictions of special geographical environments [6]. Therefore, to compensate the issue, the free space optical (FSO) communication technology would be alternative selection to replace the fiber access network [7], [8]. The FSO technology also has several benefits, such as high-speed and broad capacity, license-free, no electromagnetic interference (EMI) and signal confidentiality [9]. And the FSO capacity integrated in the PON network is also distributed from 1 to 40 Gbit/s. Furthermore, the FSO transmission would be also involved by the atmospheric turbulence, fog and rain [6], [10]. To resolve this concern, the radio frequency (RF) and FSO communication could be combined for wireless transmission. Besides, using the millimeter-wave (MMW) of 24 to 100 GHz for the 5G/B5G mobile network is the major wireless access technique in recent years [11]–[13]. In the wireless connection, the thick fog and heavy rain have the greater impact on the FSO and MMW signal, respecti vely [14], [15]. As a result, integration of baseband, FSO and MMW signals in the presented PON system would be the trend of development [16], [17].

In this demonstration, we propose and investigate an integrated optical baseband, FSO and MMW signals through the present PON architecture by employing single wavelength in the central office (CO) for broadcasting triple-play traffics.

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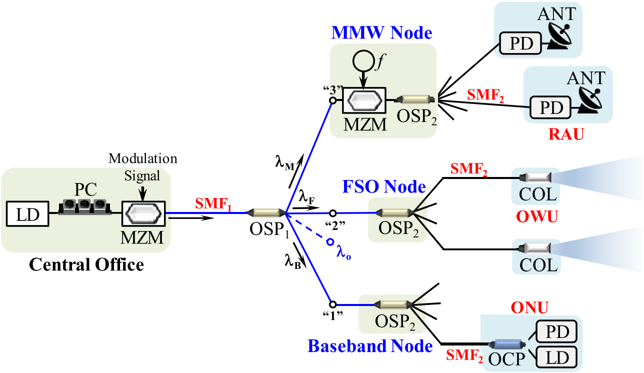

FIGURE 1. Proposed PON architecture to broadcast the baseband, FSO and MMW traffics simultaneously.

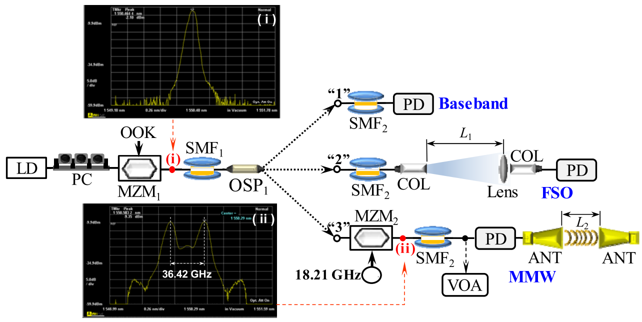

FIGURE 2. Experimental setup of proposed baseband/FSO/MMW transmission in the presented access network system.

First, we apply 10 Gbit/s OOK modulation on 10 GHz Mach-Zehnder modulator (MZM) to generate the baseband signal. Then, the 10 Gbit/s baseband signal can also produce FSO propagation under the forward error correction (FEC) target after 25 km fiber link and 160 m free space transmission. Finally, we apply the fiber to the extension (FTTE) configuration to deliver the 10 Gbit/s OOK 36.42 GHz MMW downstream after 25 km single-mode fiber (SMF) and 8 km extended fiber transmissions. As a result, a single wavelength can accomplish downstream baseband, FSO and MMW traffics simultaneously for triple-play service via our proposed PON access design.

II. EXPERIMENT AND RESULTS

Fig. 1 exhibits the presented PON architecture to deliver optical baseband, FSO and MMW signals simultaneously by utilizing single wavelength. In the central office (CO), a continuous-wave (CW) laser diode (LD) is connected to the polarization controller (PC) and 10 GHz Mach-Zehnder modulator (MZM). The modulation format can apply on MZM to generate the downstream baseband signal. Besides, we can adjust the PC to control polarization state and attain the optimal output power. Then, the downstream wavelength would transmit through a length of single-mode fiber (SMF_1) and a 1×4 optical splitter (OSP_1). Next, the modulated downstream wavelength can be separated to three signals of λ_B, λ_F and λ_M into the baseband node, FSO node and MMW node through the connected points of "1", "2" and "3", respectively, as schemed in Fig. 1. Thus, the three divided wavelengths are exploited to deliver the baseband (λ_B), FSO (λ_F) and MMW (λ_M) traffics, respectively. Moreover, the remaining wavelength (λ_0) can be utilized depending on the actual requirement which service we want.

As illustrated in Fig. 1, the wavelength λ_B will pass through a $1\times N$ OSP_2 in the baseband node and enter each optical network unit (ONU) to broadcast baseband downstream for the present PON application. And the λ_B can be detected by a PIN-based photodiode (PD). Then, the FSO wavelength λ_F will propagate through the FSO node and be emitted from the optical wireless unit (OWU) to deliver wireless FSO signal. After wireless transmission, the FSO λ_F launches into the remote OWU for signal detection, as shown in Fig. 1. Next, the wavelength λ_M can be modulated by using a 40 GHz MZM with double side-band carrier suppression (DSB-CS) modulation in the MMW node to generate dual-wavelength output. The dual-wavelength can produce the MMW signal by frequency beating in the high-speed PD [18] and be emitted from 40 GHz horn antenna (ANT) for delivering wireless MMW. However, the PON network is passive operation system. Thus, the MMW node with active component can be regarded as the fiber to the extension (FTTE) transmission for the expansion of wireless MMW. Furthermore, the splitting ratios (OSP_2) of baseband, FSO and MMW signals rely on the actual detected power budgets in the PON access. As a result, the proposed PON system can provide the baseband, FSO and MMW downstream signals simultaneously by exploiting single wavelength in the CO.

To demonstrate the signal performances of baseband, FSO and MMW traffics, respectively, an experimental setup of the proposed PON system is plotted in Fig. 2. The 1550.42 nm wavelength is used to connect to the 10 GHz MZM_1. Then, 10 Gbit/s on-off keying (OOK) modulation with pseudo random binary sequence (PRBS) of $2^{15}-1$ pattern length is applied on MZM_1 to cause the downstream signal. Here, the PC is exploited to adapt the suitably polarization situation to retain the optimal output. The output spectrum of 1550.42 nm wavelength is measured at the point of (i), as shown Fig. 2. The output power of baseband downstream wavelength is ~8 dBm at the CO in the experiment. After passing through 25 km SMF_1 transmission, the downstream wavelength can be separated by 1×4 OSP_1 and connected to the point of "1", "2" and "3" for the baseband (λ_B), FSO (λ_F) and MMW (λ_M) data links, respectively, as illustrated in Fig. 2.

As exhibited in Fig. 2, the baseband downstream traffic can be received by a 10 GHz PIN PD for measuring the bit error ratio (BER) performance via the "1" point for baseband wavelength λ_B connection. Fig. 3 indicates the measured 10 Gbit/s OOK baseband BER characteristics at the back to back (BtB) and 25 km single-mode fiber (SMF_1+SMF_2) transmission, respectively. The obtained power sensitivities are −21.8 and −22.7 dBm at the BtB state and 25 km SMF

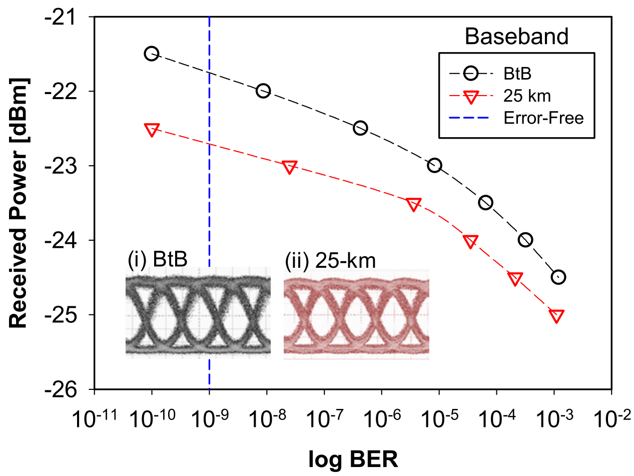

FIGURE 3. Measured 10 Gbit/s OOK baseband BER characteristics at the BtB and 25 km fiber transmission, respectively. Insets are the corresponding eye diagrams.

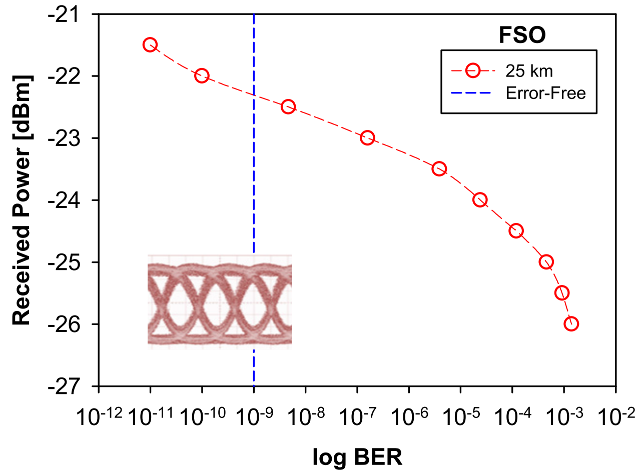

FIGURE 4. Measured 10 Gbit/s OOK FSO BER performances at the BtB and 25 km fiber transmission, respectively. Insets are the corresponding eye diagrams.

link at the BER of 1×10^{-9} in error-free state. Due to the −0.7 chirp parameter of 10 GHz MZM_1, the measured sensitivity after 25 km fiber transmission length is better than that of B2B state, as shown in Fig. 3. This is because that the negative chirp MZM_1 could pre-compensate the fiber chromatic dispersion for enhancing the power sensitivity after SMF transmission. Here, the insets of Fig. 3 are the obtained corresponding eye diagrams under the error-free. Besides, the two measured eyes are clear and open. In the measurement, to meet with the forward error correction (FEC) target of BER $\leq 3.8 \times 10^{-3}$, the corresponding power sensitivities are small than −24.5 and −25.0 dBm at the BtB and 25 km fiber link, respectively, as exhibited in Fig. 3. In addition, the detected sensitivity is −25 dBm after 25 km SMF transmission at the error-free state. Thus, the power budget of 33 dB can be reached. The baseband signal would transmit through the 25 km SMF (5 dB loss) and 1×4 OSP_1 (6 dB loss) to cause 11 dB power loss. In the measurement, the corresponding split ratio of OSP_2 can support 128 ONUs for data access.

Then, we can connect the downstream signal λ_F to the "2" point of Fig. 2 for 10 Gbit/s OOK FSO transmission. After 25 km fiber ($SMF_1 + SMF_2$) link, the 10 Gbit/s OOK downstream wavelength is coupled to a fiber collimator (COL), having 20 mm diameter, 37.13 mm focus length and 0.016° divergence angle respectively, to emit the wireless FSO signal. After 5 m free space transmission length, the divergence FSO downstream traffic can be detected by a doublet lens with 50.4 mm diameter and 75 mm focus length and launch into another COL. In this setup, an interval between the doublet lens and COL is ∼45 mm, as shown in Fig. 2. Next, the FSO signal would be coupled into fiber and enter 10 GHz PIN PD for decoding. Fig. 4 presents the obtained BER performance of 10 Gbit/s OOK FSO signal after 25 km SMF and 5 m free space length transmissions. To satisfy the error-free state, the measured power sensitivity of FSO signal is around −22.3 dBm, as illustrated in Fig. 4. The inset of Fig. 4 is the observed eye diagram at the error-free status. The FSO traffic can also achieve the FEC threshold when the obtained power sensitivity is < -26.0 dBm. In addition, the proposed FSO traffic system could also support 160 m free space link without divergence loss according to the previous simulation and experimental results [15]. Compared with the previous works [7], [17], the presented hybrid baseband/FSO/MMW PON system is novel and simple, but also can support a longer free space transmission length for data access.

Finally, we can connect the 10 Gbit/s OOK downstream wavelength via the "3" point of Fig. 2 for optical MMW connection. As plotted in Fig. 2, the 1550.42 nm downstream signal will enter the 40 GHz MZM_2. Then, we drive the MZM_2 with the DSB-CS modulation to carry an electrical sinusoidal signal at 18.21 GHz frequency by optimally adjusting the operation voltage in the MMW node. Therefore, the dual-wavelength output spectrum with 36.42 GHz mode-spacing can be obtained at the point of (ii), as illustrated in Fig. 2. After a transmission length of 8 km SMF_2, the optical signal is received in 40 GHz PIN PD via frequency beating to produce 36.42 GHz electrical MMW with 10 Gbit/s OOK and then send out from 40 GHz ATN. After 1 m wireless transmission, the MMW signal is detected by another 40 GHz horn ATN and down-converted to baseband signal for the BER measurement. Fig. 5 exhibits the obtained BERs of 10 Gbit/s OOK MMW signal versus the different received powers after passing through 8 km SMF_2 and 1 m wireless transmission. We observed that the optical power sensitivities are −1.3 and −1.5 dBm at the BtB and 8 km SMF_2 transmission, respectively. Furthermore, the insets of Fig. 5 are the observed corresponding eye diagrams. As shown in Fig. 5, the power penalty of 0.2 dB can be observed under error-free status. Moreover, to reach the FEC target (BER $\leq 3.8 \times 10^{-3}$), the measured sensitivities can be smaller than −6 dBm in the experiment. Since the fiber length is only 8 km and the

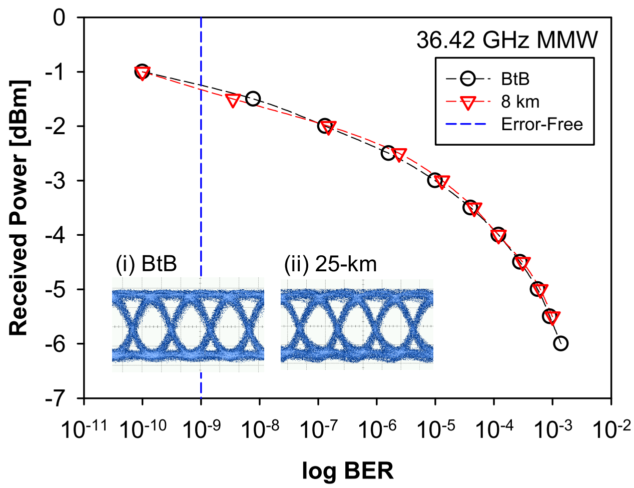

FIGURE 5. Measured 10 Gbit/s OOK MMW BER performances at the BtB and 25 + 8 km fiber link, respectively. Insets are the corresponding eye diagrams.

radio-over-fiber signal is only 36.42 GHz in the proposed FTTE scheme, the RF fading effect can be negligible in the fiber transmission length.

Based on the presented integrated optical baseband, FSO and MMW PON access network, we can only utilize single wavelength in the CO to deliver three different 10 Gbit/s downstream signals for broadcasting triple-play services. Therefore, we can rely on the different environments and needs of network deployments to decide the suitably baseband, FSO and MMW traffic for the use of end-user. Furthermore, we can also integrate the WDM channels in the CO to enhance the data capacity of multi-play service in the proposed PON architecture.

III. CONCLUSION

Using single wavelength in the CO to deliver the baseband, FSO and MMW signals simultaneously in the PON network for the triple-play service was investigated experimentally. In the demonstration, the 10 Gbit/s OOK baseband wavelength could also be utilized to serve as the FSO and MMW signals for broadcasting the three different communication traffics through the present PON access architecture. The obtained sensitivities of baseband channel were −21.8 and −22.7 dBm under the error-free status at the BtB and 25 km fiber transmission, respectively. Here, we utilized the −0.7 chirp MZM to pre-compensate the fiber dispersion for improving the attained optical sensitivity and enhancing the power budget in PON network.

The 10 Gbit/s OOK baseband channel was also regarded as the FSO traffic in the presented PON system. The observed sensitivity of FSO signal was −22.3 dBm under the BER of 1×10^{-9} after passing through 25 km fiber link and 5 m wireless transmission length. Moreover, the wireless FSO channel could also accomplish 160 m free space traffic link without divergence loss based on our designed optical system. In practical FSO system, the fog, rain and turbulence would also influence the FSO performance [14], [15]. Hence, the enough power budget of FSO channel could support the properly wireless transmission length and data performance.

To exploit the 10 Gbit/s OOK baseband channel effectively for delivering 36.42 GHz MMW traffic, we could apply the FTTE connection in the proposed PON network simultaneously. Based on the DSB-CS modulation in the MMW node, the optical MMW signal could be induced by frequency beating approach in the 40 GHz high-speed PD. After 33 km SMF (25 km SMF_1+ 8 km SMF_2) transmission and 1 m wireless MMW propagation, the corresponding optical sensitivities of −1.3 and −1.5 dBm were acquired at the BtB and 33 km SMF link under error-free level, respectively.

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CHIEN-HUNG YEH received the Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2004. In 2004, he joined the Information and Communications Research Laboratories (ICL), Industrial Technology Research Institute (ITRI), Taiwan, as a Researcher, where he was promoted to a Principal Researcher for leading the ITRI Industrial-Academic Projects, in 2008. In 2014, he joined the Faculty of Department of Photonics, Feng Chia University, Taiwan, where he is currently a Professor. His research interests include optical fiber communication, fiber laser and amplifier, PON access, MMW communication, fiber sensor, and VLC and FSO (Li-Fi) communications.

WEN-PIAO LIN received the Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2002. From 1985 to 1987, he joined Hua-Eng Company, Kaohsiung, Taiwan, where he engaged in research in the area of optical fiber subscriber loops. In 2003, he joined the Faculty of Department of Electrical Engineering, Chang Gung University, Taoyunan, Taiwan, where he is currently a Full Professor. His current research interests include EDF-based tunable ring fiber lasers and photonic millimeter-wave radio-over-fiber access networks.

CHIEN-MING LUO received the B.S. degree from the Department of Electronics, Cheng Shiu University, Taiwan, in 2018. He is currently pursuing the M.S. degree with the Department of Photonics, Feng Chia University, Taiwan.

YUE-RU XIE received the B.S. degree from the Department of Photonics, Feng Chia University, Taiwan, in 2016, where he is currently pursuing the M.S. degree.

YAO-JEN CHANG received the B.S. and M.S degrees from the Department of Photonics, Feng Chia University, Taiwan, in 2017 and 2019.

CHI-WAI CHOW received the B.Eng. (Hons.) and Ph.D. degrees from the Department of Electronic Engineering, The Chinese University of Hong Kong (CUHK), in 2001 and 2004, respectively. His Ph.D. work was focused on optical label controlled packet switched networks. After graduation, he was appointed as a Postdoctoral Fellow with the CUHK, involved in hybrid integration of photonic components and silicon waveguides. From 2005 to 2007, he was a Postdoctoral Research Scientist, working mainly on two European Union Projects: Photonic Integrated Extended Metro and Access Network (PIEMAN) and Transparent Ring Interconnection Using Multi-wavelength Photonic Switches (TRIUMPH), with the Tyndall National Institute and Department of Physics, University College Cork (UCC), Ireland. In August 2007, he joined the Department of Photonics, National Chiao Tung University (NCTU), Taiwan, where he is currently a Professor.