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A Simple WDM-PON Architecture Together With Private Interconnected ONUs

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ABSTRACT In this paper, we present and investigate a wavelength-division-multiplexing passive optical network (WDM-PON) with symmetrical 28 Gbit/s on-off keying (OOK) access signals and 3 Gbit/s virtual private network (VPN) link between the optical network units (ONUs) simultaneously. To achieve the VPN connection, a ring-based network architecture is designed to link every ONU. Here, a direct modulation laser diode (LD) of 1311.6 nm wavelength is applied in ONU for VPN transmission to separate from PON network. In the investigation, the fiber and free space optical communication (FSO) based connections are also exploited to connect every ONU. In addition, the corresponding signal behaviors of WDM-PON and VPN networks are also analyzed and discussed.

INDEX TERMS WDM-PON, virtual private network (VPN), Rayleigh backscattering (RB), OOK modulation, confidential connection.

I. INTRODUCTION

Lately, in order to achieve and support the multi-service of artificial intelligence (AI), big data, cloud access, video on demand, 4K/8K video, online gaming, and 5G/6G wireless mobile, the passive optical network (PON) system would be the potential choice in the last mile access for end-user [1], [2]. Furthermore, the wavelength-division-multiplexing (WDM) access techniques could provide the huge data capacity, high flexibility, long-reach connection, and extended coverage [3]–[5]. The WDM-PON is a point to point (PtP) network. Hence, the multiple WDM wavelengths are required to regard as the downstream and upstream signals. Once the downstream and upstream signals are the same wavelengths for bidirectional connection, the Rayleigh backscattering (RB) would be induced to cause the interference noise at the photodiode (PD) of optical line termination (OLT) and optical network unit (ONU), respectively [6]. To avoid the RB noise, using dual band for dividing the downstream and upstream traffics over available wavelength bandwidth is the common way basically [7]. Furthermore, to achieve seamless signal in PON

access, using free space optical (FSO) communication techniques in PON networks have been also studied based on some geographical restrictions and its ease of deployment recently [8], [9].

Additionally, to provide high-speed and high-quality private networking among the ONUs for end-users in such PON simultaneously, applying the virtual private network (VPN) connection could be a promising method for this issue [10]. However, the usual WDM-PON system cannot support the direct signal connection between the ONUs. Thus, the inter-ONU data link in the PON network needs to be connected to the OLT and reflected to ONUs through the arranging and routing process in the media access control (MAC) [11]. This mechanism would result in the information delay in VPN link, congestion of signal process at the OLT and bandwidth consumption of downstream and upstream signals. To achieve the physical layer VPN in PON system, several optical network schemes have been studied and experimentally demonstrated [10]–[13].

In this paper, we propose and investigate a new VPN scheme, which can be integrated in original WDM-PON for proof of concept. Here, the presented WDM-PON can not only use optical fiber to connect ONU, but also can exploit FSO technique under special circumstances. In the

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demonstration, symmetrical 28 Gbit/s on-off keying (OOK) downstream and upstream wavelengths are achieved within the forward error correction (FEC) level after 25 km single-mode fiber (SMF) transmission. Besides, the proposed WDM-PON also can reach 28 Gbit/s OOK FSO through 25 km SMF and 2 m FSO transmissions under the FEC target. Then, to achieve the VPN operation in PON, we can apply the ring-based fiber connection between all the ONUs via simple module scheme. A direct modulated laser diode (LD) of 1311.6 nm wavelength, a 3 GHz PIN photodiode (PD) and a 4-port optical circulator (OC) are added in each ONU for private interconnection. Therefore, the VPN signal among the ONUs can reach 3 Gbit/s OOK direct modulation after 26 km SMF link without any amplification.

II. EXPERIMENT AND RESULTS

To obtain the interconnected ONUs in the presented WDM-PON system simultaneously, a simple network architecture is demonstrated for proof of concept as schemed in Fig. 1(a). In the PON, we design a ring-based fiber connection to link every ONU for providing interconnection simultaneously. Thus, all the ONUs also can result in a virtual private network (VPN) in the presented WDM-PON. Here, we apply a 1 × 4 array waveguide grating (AWG) at the optical line termination (OLT) and remote node (RN) serving as the wavelength multiplexer (MUX) and demultiplexer (DEMUX), respectively. In the WDM-PON, the downstream wavelengths of λ₁ to λ₄ and the upstream wavelengths of λ₅ to λ₈ are applied for the signal links of ONU1 to ONU4 based on the spectra periodicity of AWG, respectively. In addition to the use of optical fiber to transmit access signals, the FSO connection is also one of the ways as seen in Fig. 1(a), when some environmental limit or special consideration [14]. The VPN system does not necessarily need to be composed of all ONUs in practical state. The PON system also can produce several VPN groups, which are composed of several ONUs with common requirements. In Fig. 1(b), the ONU1 and ONU2, and ONU3 and ONU4 can also be constructed two different VPNs in PON for particular needs, respectively. Simply put, a VPN network can be composed of two or more ONUs.

Fig. 2 exhibits the proposed ring-based connection VPN network in the presented WDM-PON system in detail. To provide a higher capacity downstream signal here, a 40 GHz Mach-Zehnder modulator (MZM_{40G}) is connected to each WDM wavelength to generate 28 Gbit/s on-off keying (OOK) modulation data by bit error rate tester (BERT) in the OLT. Here, after 25 km SMF transmission, the WDM downstream signals of λ₁ to λ₄ will enter every corresponding ONU and then into a 40 GHz PIN photodiode (PD) through an optical circulator (OC) for demodulation, as seen in Fig. 2. To reach the symmetrical 28 Gbit/s OOK upstream traffic, we can also use the MZM_{40G} at each ONU. As seen in Fig. 2, the polarization controller (PC) is applied to adjust the optimal polarization state and output power in the experiment.

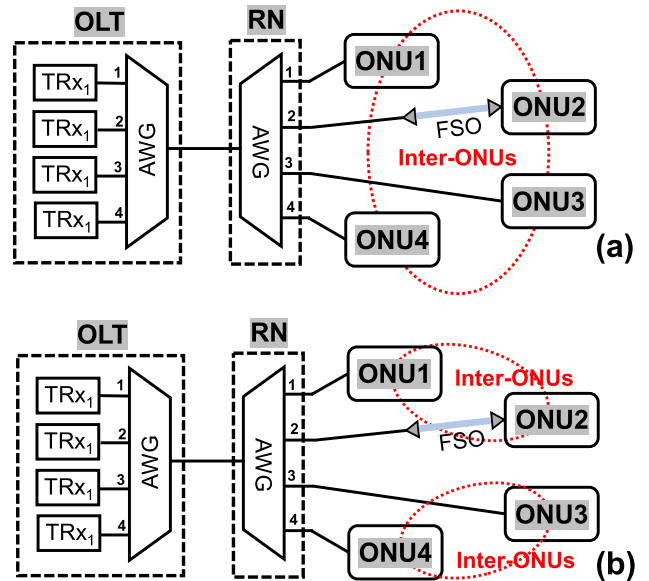


FIGURE 1. Proposed fiber and FSO based WDM-PON system with ring-based VPN connection (a) between all ONUs and (b) different ONU groups, respectively.

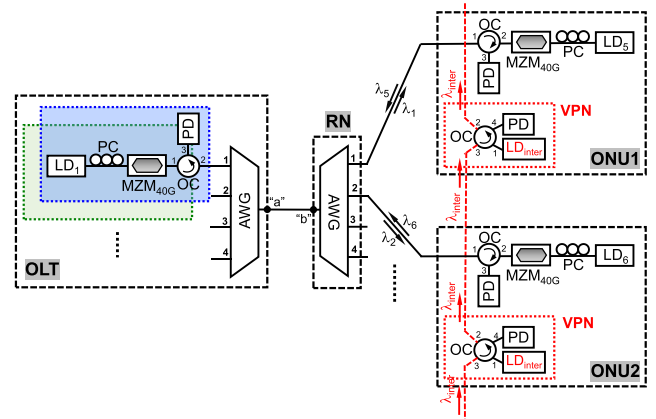


FIGURE 2. Detailed ONU module for VPN connection in proposed WDM-PON architecture.

Moreover, to create the VPN connection in the PON network, the additional 3 GHz direct modulated laser diode (LD_{inter}) of 1311.6 nm, 3 GHz PIN PD, and four-port OC is added in every ONU for private signal connection. 3 Gbit/s OOK VPN signal (λ_{inter}) can be generated by the 1.3 μm LD_{inter} for every interconnected ONUs. In the demonstration, suppose the WDM-PON system has four ONUs for VPN link and will not be transmitted via the OLT. As illustrated in Fig. 2, the interconnected signal λ_{inter} of ONU will deliver one by one in unidirectional signal propagation. Therefore, the λ_{inter} signal connected to the other ONU needs to go through a round of transmission and signal processing before it can be received. While the ONU1 want to deliver λ_{inter} signal to ONU2, the data traffic needs to enter the ONU4 and ONU3 respectively for signal processing via proper dynamic bandwidth allocation (DBA) algorithm and then into ONU2,

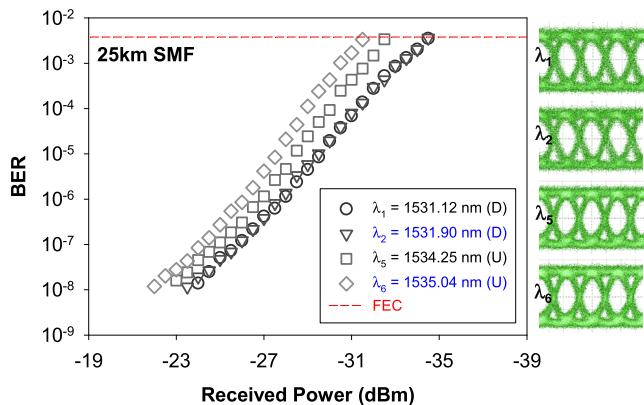


FIGURE 3. Measured 28 Gbit/s OOK BER behaviors of downstream (λ_1 and λ_5) and upstream wavelengths (λ_2 and λ_6) in the proposed WDM-PON after 25 km SMF transmission, respectively. Insets are the observed eye diagrams at the largest received powers.

as schemed in Fig. 2. In addition, if a VPN network is formed by two ONUs in the PON, the λ_{inter} of ONU would become a peer-to-peer connection based on the proposed ring-based configuration.

First, the downstream and upstream signals of 1531.12 (λ_1) and 1534.25 nm (λ_5), and 1531.90 (λ_2) and 1535.04 nm (λ_6) are applied in the ONU1 and ONU2 for bit error rate (BER) measurements, respectively. Here, the output power of downstream signals both are 7.5 dBm at the “a” point of Fig. 2. Besides, the upstream signal is also set at 7.5 dBm after leaving OC. Fig. 3 exhibit the measured 28 Gbit/s OOK BER performances of selected four wavelengths through 25 km SMF transmission, respectively. A dispersion compensation module (DCM) is put at the “d” point of Fig. 2 to compensate the chromatic fiber dispersion. An optical pre-amplifier can be operated in front of PD to amplify the power and enhance the observed sensitivity. To meet with the forward error correction (FEC) level at the BER of $\leq 3.8 \times 10^{-3}$, the detected power sensitivities of λ_1 , λ_2 , λ_5 and λ_6 are -34.5 , -34.5 , -32.5 and -31.5 dBm, respectively. The insets are observed corresponding eye diagrams of λ_1 to λ_6 at the greatest received powers of Fig. 3. According to the proposed PON system, the total insertion loss of 17.5 dB is induced by 25 km SMF ($0.2 \text{ dB/km} \times 25 = 5 \text{ dB}$), an AWG (6 dB), a DCM (6 dB) and an OC (0.5 dB), respectively. Thus, the achieved power budgets of the four signals are 42, 42, 40 and 39 dB, respectively. And the redundant power budgets of 24.5, 24.5, 22.5 and 21.5 dB are obtained in proposed the WDM-PON with VPN link.

Then, we verify the BER performance of VPN signal λ_{inter} . The output power of λ_{inter} is 2.4 dBm at each ONU. The measured BER of 3 Gbit/s OOK VPN signal after 25 and 26 km SMF connections, respectively, when the VPN network has only two ONUs. Two measured BER curves are similar. The obtained power sensitivities both are -13.5 dBm under the FEC threshold through two various SMF lengths without using amplifier. Moreover, the insets of two corresponding eye diagrams both are measured at -9 dBm. Here, a length

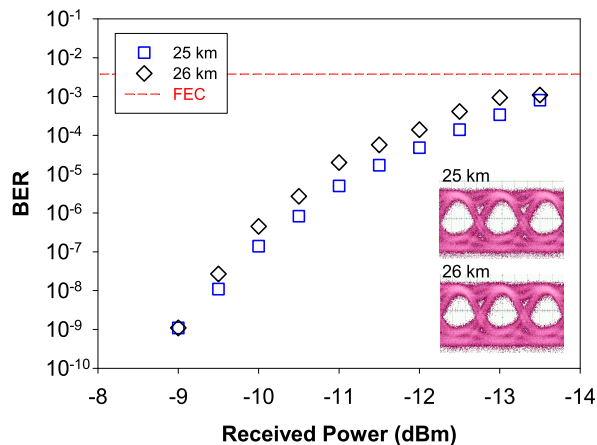


FIGURE 4. Obtained BER performance of 3 Gbit/s OOK VPN signal after 25 and 26 km SMF connection, respectively. Insets are the corresponding eye diagrams at -9 dBm received power.

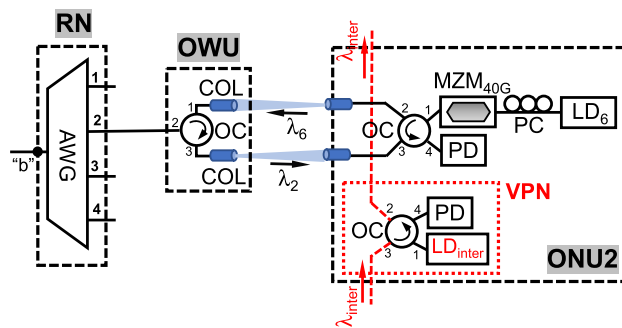


FIGURE 5. Schematic of FSO transmissions of downstream and upstream between OWU and ONU.

of 26 km SMF ($0.3 \text{ dB/km} \times 26 \text{ km} = 7.8 \text{ dB}$) and two OCs ($0.5 \text{ dB} \times 2 = 1 \text{ dB}$) would induce the total insertion loss of 8.8 dB. In the demonstration, a power budget of 15.9 dB can be achieved within the FEC target. In general, the length of the SMF transmission between ONUs will not be too long for VPN link. Hence, the proposed VPN ring-based link in PON network can be achieved by using the 1311.6 nm direct modulated LD_{inter} under sufficient power budget. In addition, the various fiber lengths of PON and VPN architectures will result in different transmission latencies, which can be expressed by $t_{latency} = (L/c) \cdot n$, where L , c and n are the fiber length, speed of light in vacuum and average index of single-mode fiber, respectively.

To satisfy the geographical limitation, we also can use the FSO technique to connect the bidirectional signals in PON network. As seen in Fig. 5, we can build an optical network unit (OWU), which is constructed by an OC and two fiber-type collimators (COLs) to connect the ONU2, at proper location for the wireless FSO link. The OCs of OWU and ONU2 are applied to isolate the downstream and upstream wavelengths for data connection, as schemed in Fig. 5. Here, the COL has the diameter, focal length and divergence angle of 20 mm, 37.13 cm, and 0.016° , respectively. To facilitate

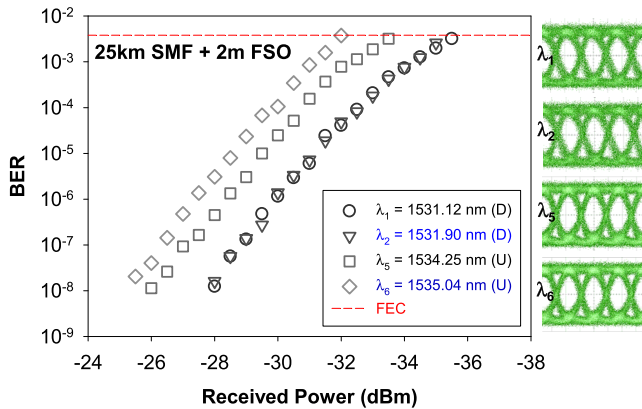


FIGURE 6. Measured 28 Gbit/s OOK BER behaviors of downstream (λ_1 and λ_5) and upstream wavelengths (λ_2 and λ_6) in the proposed WDM-PON through 25 km SMF and 2 m FSO transmissions, respectively. Insets are the observed eye diagrams at the largest received powers.

FSO signal connection, the wireless length is set at 2 m for proof of concept. The measured insertion loss between two COLs at the OWU and ONU2 is around 3 dB. In the experiment, the total loss of 21 dB is caused by 25 km SMF ($0.2 \text{ dB/km} \times 25 \text{ km} = 5 \text{ dB}$), an AWG (6 dB), two OCs ($0.5 \text{ dB} \times 2 = 1 \text{ dB}$), a DCM (6 dB) and FSO link (3 dB), respectively, in the FSO-based PON. The output powers of downstream and upstream wavelengths are the same as mentioned above.

Fig. 6 display the measured 28 Gbit/s OOK BER behaviors of downstream and upstream signals of λ_1 and λ_5 and λ_2 and λ_6 at the ONU1 and ONU2, respectively, through 25 km SMF and 2 m wireless FSO connections. We observe that the corresponding power sensitivities of $\lambda_1, \lambda_2, \lambda_5$ and λ_6 are $-35.5, -35, -33.5$ and -32 dB under the FEC level, respectively. So, the related power budgets are 43, 42.5, 41 and 39.5 dB, respectively. The redundant budgets of 22, 21.5, 20 and 18.5 dB can be used to estimate the free space transmission length between OWU and ONU without using optical amplification for optimal design [14]. In addition, the insets of Fig. 6 are the observed eye diagrams of four selected wavelengths at the smallest received powers, respectively. These measured eyes are clean and open significantly after SMF and FSO transmission.

III. CONCLUSION

We demonstrated a WDM-PON system with VPN link between the entire ONUs simultaneously. Here, the symmetrical 28 Gbit/s OOK downstream and upstream wavelengths were achieved when dual-band wavelengths were applied for separation based on the spectral periodicity of AWG. Thus, the different downstream and upstream wavelengths in the PON could avoid the RB-induced beat noise. In the demonstration, four wavelengths of λ_1 and λ_5 and λ_2 and λ_6 were selected to deliver downstream and upstream traffics for BER measurements, respectively. Through 25 km SMF

transmission, the obtained power sensitivities would result in enough power budgets to satisfy the total insertion loss of presented PON system. Moreover, even after 25 km SMF and 2 m FSO transmissions, the achieved power budgets were still larger than the total loss. According to the redundant power budget could estimate the available FSO length between OWU and ONU.

To accomplish the VPN transmission between the entire ONUs in the presented PON simultaneously, a ring-based fiber connection was designed. The additional devices of 1311.6 nm LD with 3 GHz bandwidth, 3 GHz PD and 4-port OC were also requested in each ONU. Besides, 3 Gbit/s OOK direct modulation VPN signal was obtained through 26 km SMF link to meet with the FEC target without optical amplification.

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