Reconfigurable and Scalable All-Optical VPN in WDM PON

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***Abstract*—In this letter, we propose and experimentally demonstrate an all-optical virtual private network (VPN) structure in a wavelength-division-multiplexed (WDM) passive optical network (PON). The scheme utilizes a semiconductor optical amplifier (SOA) in optical line terminal (OLT) to transfer optical VPN data among different optical network units (ONUs) based on the cross-gain-modulation (XGM) effect. By dynamically copying the optical VPN signal onto different wavelengths, the optical VPN can be reconfigured.**

***Index Terms*—Cross-gain modulation (XGM), passive optical network (PON), semiconductor optical amplifier (SOA), virtual private network (VPN), wavelength-division-multiplexed (WDM).**

I. Introduction

ALL-OPTICAL virtual private network (VPN) [1] is a promising approach to provide dedicated optical channels to connect end users with high bandwidth efficiency and enhanced security compared to traditional VPN using IP protocol. Passive optical network (PON) technology, taking its advantages of broadband access, large coverage area and cost-effective configuration, is believed to be a good platform to support optical VPN service access with high throughput and low latency. In previous reports, all-optical VPNs in PONs have been demonstrated based on wavelength reflection or star couplers [2], [3]. To provide optical VPN service in a wider covering area, two schemes were proposed in [4], [5] to connect optical network units (ONUs) in different PONs. However, these two demonstrated schemes employed a special architecture, which may not be practical in applications. In addition, reconfiguration is important in dynamical networks to allow new users to intercommunicate with others. Reference [6] presented a reconfigurable optical VPN scheme in a wavelength-division-multiplexed (WDM) PON using tunable transmitter, which can only deliver optical VPN service between two ONUs.

In this letter, we propose and experimentally demonstrate a reconfigurable and scalable all-optical VPN in a WDM PON system, which can realize intercommunications within multiple ONUs. In this scheme, a number of differential phase-shift keying (DPSK) upstream signals and an optical VPN signal in amplitude-shift keying (ASK) format are respectively generated in ONUs and transmitted to the optical line terminal (OLT). At the OLT, a commercial semiconductor optical amplifier (SOA) is used to convert the optical VPN data to the wavelengths carrying upstream signals to form an all-optical VPN. By selectively feeding different wavelengths into the SOA, one can simply reconfigure the all-optical VPN among different ONUs. Compared to the previous schemes, our proposal enables convenient reconfiguration of VPN connections and serves more ONUs in a WDM PON.

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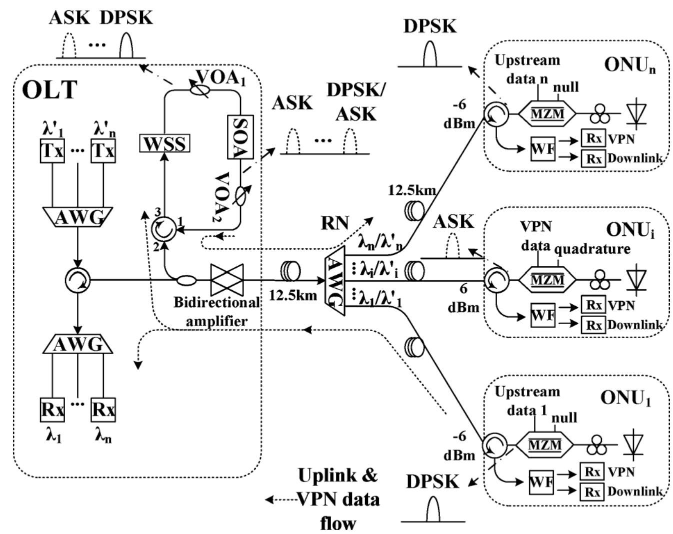

Fig. 1. Reconfigurable and scalable optical VPN scheme in WDM PON (WF: waveband filter).

II. Principle

The schematic diagram of the proposed all-optical VPN structure in an n-wavelength WDM PON system is depicted in Fig. 1. In our scheme, a single Mach–Zehnder modulator (MZM) in each ONU is biased at the transmission null point to generate the upstream signal in the DPSK format. When ONU$_i$ wants to establish an all-optical VPN with some other $m-1$ ONUs, it firstly sends a control message to the OLT. Then the OLT inquires the $m-1$ ONUs whether they agree to join the VPN. If they do, $m-1$ ONUs send the upstream carriers with or without upstream data. Simultaneously, the MZM in the ONU$_i$ is biased at the quadrature point and modulated by the optical VPN data instead of the upstream data to produce an ASK signal. After transmitting through a 12.5-km distribution fiber, all the wavelengths are multiplexed by a cyclic arrayed waveguide grating-router (AWG) at remote node (RN) and then launched into a 12.5-km feeder fiber. At the OLT, a bidirectional amplifier is used to compensate for the transmission loss.

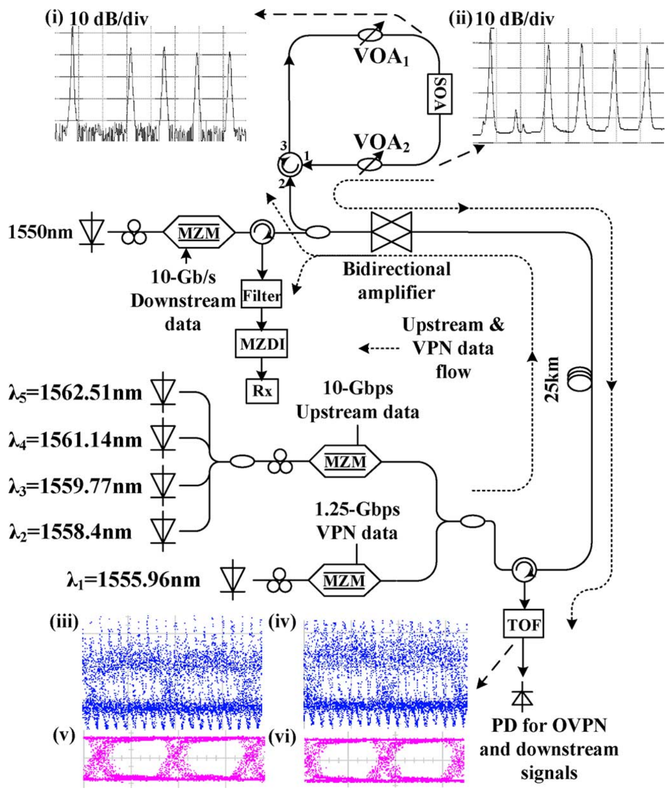

Fig. 2. Experimental setup and results. (i) Spectrum before SOA. (ii) Spectrum after SOA. (iii) Eye diagram at λ_2. (iv) Eye diagram at λ_4. (v) Eye diagram after 2.5-GHz PD at λ_2. (vi) Eye diagram after 2.5-GHz PD at λ_4.

The amplified signals are split into two parts by a 1×2 optical coupler. One part is directly detected by DPSK receivers to recover the upstream data carried in the DPSK format. The other part goes through a loop consisting of a circulator, a wavelength selective switch (WSS), two variable optical attenuators (VOAs) and an SOA. Using the WSS, m wavelengths in all-optical VPN are selected and injected into the SOA. The VPN signal with the ASK format at λ_i is copied onto the other $m-1$ upstream DPSK signals using the cross-gain modulation (XGM) effect in the SOA to generate orthogonal ASK/DPSK signals carrying optical VPN data. Through the VOA, the circulator, the optical coupler and the bidirectional amplifier, the m amplified VPN signals are launched into the feeder fiber. Here, the VOAs are used to control the input powers of the signals injected into the SOA and bidirectional amplifier. At the RN, the signals are demultiplexed by the cyclic AWG and delivered to the individual ONUs. Thus, an all-optical VPN in m ONUs is realized.

III. Experimental Setup and Results

Fig. 2 shows the experimental setup used to provide all-optical VPN service in five ONUs with different wavelengths in a WDM PON. At the ONU side, a 10-GHz MZM is utilized to modulate a continuous wave (CW) light from a tunable laser at λ_1 (1555.96 nm). The 1.25-Gb/s pseudorandom bit sequence (PRBS) VPN data drives the MZM to generate the optical VPN signal in the ASK format. A second 10-GHz single MZM is employed to modulate four CW lights from distributed feedback (DFB) array lasers with wavelengths at λ_2 (1558.4 nm), λ_3 (1559.77 nm), λ_4 (1561.14 nm), and λ_5 (1562.51 nm), respectively. The MZM is biased at the null point and driven by a 10-Gb/s PRBS upstream data to produce four DPSK signals. In the experiment, the two PRBS data are respectively obtained from the front panel and the rear panel (1/8 output ports) of a pulse pattern generator (PPG) (ANRITSU MP1763c) with the same word length of $2^7 - 1$, due to the PPG setting limitation when the rear panel 1/8 output is desired to maintain PRBS. By adjusting the driving and bias currents for lasers, the output powers of the two MZMs are maintained to 6 dBm and 0 dBm, respectively. The power difference between the upstream signals and VPN signal is controlled to facilitate the wavelength conversion using XGM effect in the SOA in the OLT. Through a 1×2 optical coupler, the optical VPN and upstream signals are coupled and launched into a 25-km standard single-mode fiber (SMF) instead of the 12.5-km distribution fiber and the 12.5-km feeder fiber. At the OLT, the signals are split into two parts by another 1×2 optical coupler after amplification. One part passes through a circulator, a filter and a Mach–Zehnder delay interferometer (MZDI), and is detected by upstream receivers to retrieve the upstream data. The other part goes through a second circulator, two VOAs and an SOA. By properly adjusting the VOA$_1$, the upstream DPSK signals at $\lambda_2 \ldots \lambda_5$ with a total power of 0 dBm are coupled with the optical VPN ASK signal of 6 dBm, and then they are fed into a commercial SOA (SOA-NL-OEC-1550 from CIP). The insets (i) and (ii) in Fig. 2 show the spectra before and after the SOA. There are certain out-of-band four-wave-mixing (FWM) components in inset (ii), which are about 25 dB lower than the signals. Due to the XGM effect, four signals at wavelengths $\lambda_2 \ldots \lambda_5$ carrying the inversed VPN data are obtained at the output of the SOA.

After 25-km transmission, in the ONU, a tunable optical filter (TOF) is used to separate each wavelength carrying VPN data, which is received by a following 2.5-GHz photodetector (PD). The insets (iii) and (iv) in Fig. 2 illustrate the eye diagrams for the VPN signals at wavelengths λ_2 and λ_4 after the transmission. Due to the interference of the 10-Gb/s upstream DPSK signals, the eye diagrams of the signals exhibit 10-GHz ripples. After detected by the 2.5-GHz PD, the ripples can be effectively removed and the eye diagrams with wide opening are provided in the insets (v) and (vi).

Fig. 3(a) and (b) show the bit-error-ratio (BER) curves for the optical VPN signals at λ_2 and λ_4. About 0.7-dB power penalty is observed for the optical VPN data at both wavelengths after the transmission. For the upstream DPSK signals, the power penalty is about 0.4 dB after the 25-km transmission as shown in Fig. 3(c).

In the downstream case, an ASK signal on a different waveband is generated by driving the MZM with a 10-Gb/s PRBS data of $2^{31} - 1$ length. The signal travels from the OLT to the ONUs where it is filtered by the optical filter and received by a 10-GHz receiver (Rx). The BER curve is shown in Fig. 3(d).

In the experiment, we switch off λ_3 and λ_4 before the signals are fed into the SOA, and an optical VPN among the other three wavelengths is achieved. Similarly, if one change the wavelengths of the five CW light sources or inject more than five wavelengths into the SOA, another optical VPN can be realized

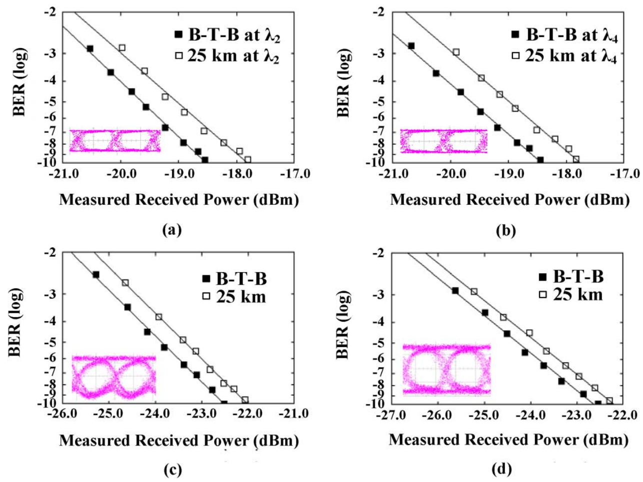

Fig. 3. (a) BER curves for OVPN data at λ_2, (b) OVPN data at λ_4, (c) upstream data, and (d) downstream data.

TABLE I
POWER BUDGET CALCULATIONS USING THE MEASURED EXPERIMENTAL PARAMETERS

	VPN traffic	Upstream traffic
Transmitted power at ONUs (dBm)	6	-6
Circulator loss (dB)	2	2
12.5-km distribution fiber loss (dB)	3	3
Cyclic AWG loss (dB)	6/2.5	6/2.5
Splitter loss (dB)	$3\lg_2 N$	0
12.5-km feeder fiber loss (dB)	3	3
Saturated output power of amplifier (dBm)	24	24
Optical coupler loss (dB)	4	4
Power penalty induced by RB effect	0.2/0	10/1
Sensitivity at BER = 10^{-9} (dBm)	-18	-22
Power Margin (dB)	$13.8\text{-}3\lg_2 N$	3/12

using the XGM effect [7]. In practice, one can employ a WSS to select the wavelengths and thus realize a reconfigurable optical VPN within multiple ONUs using different wavelengths.

IV. SCALABILITY ANALYSIS

In this section, we analyze the scalability of our proposal using the measured experimental parameters shown in Table I. Here, we define the power margin as the difference between the received optical power and the minimum optical power that is required by the receiver to achieve a BER of 10^{-9}. The transmitted powers at the output ports of the ONUs are 6 dBm for the optical VPN signal and -6 dBm for upstream signals. The total transmission loss between the ONU and the OLT is about 12 dB. After passing through the bidirectional amplifier, the optical coupler and the AWG, the signal wavelengths are dynamically chosen by a set of switches. By properly adjusting the VOA_1, the selected signals carrying upstream data are fed into the SOA with the original VPN signal. As the SOA operates in the saturation region, a saturated gain of 10 dB is obtained for the converted signals. Similarly, with appropriate adjustment of VOA_2, the converted signals have a power of 10 dBm at the output port of the OLT, which would not induce much nonlinear effects. After transmission, the received power of the PD for detecting VPN data is -4 dBm. In Fig. 3, we observe a sensitivity of about -18 dBm at a BER of 10^{-9} for the optical VPN signals in 1-to-4 wavelength conversion. If two-stage SOAs were used to replace the SOA in our experiment to alleviate the waveform distortion, the received optical power for a BER of 10^{-9} could remain -18 dBm in 1-to-16 wavelength conversion [7]. Considering a power penalty of $\sim$0.2 dB caused by Rayleigh backscattering (RB) effect in the OLT, the power margin of $13.8\text{-}3\lg_2 N$ dB for VPN signals is achieved, where N is the number of the ONUs in the all-optical VPN. Thus, by using two-stage SOAs, our scheme could support an optical VPN within 16 ONUs in a 128-channel WDM PON while keeping power margins of 1.8 dB for VPN signals and 3 dB for upstream signals, respectively. In order to mitigate the RB effect for upstream signals, a low-loss AWG ($\sim$2.5 dB) [8] can be utilized to reduce the transmission loss, which can increase signal to RB ratio to 25 dB and decrease the power penalty to 1 dB [9].

V. CONCLUSION

We have proposed a reconfigurable and scalable all-optical VPN architecture in a 10-Gb/s WDM PON, and experimentally demonstrated the optical VPN data transmission in five ONUs with a data rate of 1.25 Gb/s. The optical VPN data transfer among different ONUs is realized by the XGM effect of the SOA at the OLT. With the use of the WSS, the optical VPN can be conveniently reconfigured within different ONUs. Scalability analysis shows that our scheme can support optical VPN services among 16 ONUs in a 128-channel WDM PON if two-stage SOAs were employed.

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