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Centrally controlled self-healing wavelength division multiplexing passive optical network based on optical carrier suppression technique

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Abstract. We proposed and demonstrated a centrally controlled and self-healing wavelength division multiplexing passive optical network with colorless optical network units (ONUs) based on optical carrier suppression technique. By switching the affected data in the OCS signal sideband to an alternate protection path, only one optical switch is provisioned at the optical line terminal, which is controlled by a logic control circuit upon monitoring of power outage on the working path. The proposed scheme can reliably protect against both distribution and feeder fiber failures. Moreover, gain-saturated reflective semiconductor optical amplifiers are used as colorless transmitters in ONUs. The protection scheme feasibility and system performances are experimentally verified with 10 Gb/s downstream and 1.25 Gb/s upstream data in both working and protection modes. The protection switching time was measured to be around 1 ms. [DOI: 10.1117/1.OE.54.12.126105]

Keywords: optical carrier suppression; wavelength division multiplexing passive optical network; self-healing; reflective semiconductor optical amplifier.

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1 Introduction

Wavelength division multiplexed passive optical network (WDM-PON) is broadly viewed as a promising solution for future broadband access networks.[1] With the rapid increase of WDM-PON transmission capacity, any possible failure of either feeder fibers (FFs) or distribution fibers (DFs) will lead to a large amount of data losses. Thus, failure monitoring and network protection are imperative for network operators to enhance the network reliability.[2]

So far, several protection schemes against fiber fault for WDM-PONs have been proposed,[3–7] which switch the affected data to an alternate protection path upon the monitoring of a power outage on the working path. According to the placement of the control intelligence, one category is called "distributed control."[3,4] A monitoring and control unit (MCU) and an associated optical switch (OS) are installed at each optical network unit (ONU), which increases the complexity and cost of ONUs. In yet another category of these schemes termed as "central control," the centralized protection switching is performed in the optical line terminal (OLT).[4–6] However, an additional dedicated light source for protection switching is needed for each wavelength channel. Moreover, the wavelength-dependent ONUs comprised of a local laser for upstream (US) transmission is also not desirable in WDM-PONs. In Ref. 7, $2N$ interleavers (ILs) and N OSs (together with N MCUs) are required in the OLT, which greatly increases the system's complexity. The optical carrier suppression (OCS) technique was employed to generate two optical subcarriers just for bidirectional transmissions, not for protection switching. In each channel, two optical couplers (OCs) were used to realize the clockwise wavelength sharing scheme for protection switching, which increase the downstream (DS) power loss by 6 dB. In Ref. 8, the OCS technique is applied to setup the alternate protection path without additional dedicated light source for protection switching, but the clock signal for the OCS technique is required to be at least 25 GHz or above at the transmitter side to alleviate the beating effect at the receiver side. In addition, N electronic switches and N MCUs are also installed in the OLT, which also increases the system complexity.

In this paper, we proposed a centrally controlled, self-healing WDM-PON with N colorless ONUs. The proposed protection scheme can protect DS and US links against both FF and DF failures by applying the OCS technique to a multiwavelength light source (MLS) at the OLT. It is different from all the above-mentioned protection schemes in that only one 1×2 OS is required at the OLT, which switches the affected normal path to an alternate protection path by utilizing a logic decision unit based on the monitoring results for received power on the respective US link. Additionally, gain-saturated RSOAs are used as colorless transmitters in ONUs. No additional dedicated light source for protection switching is needed. Such architecture not only simplifies the ONU design, but also significantly reduces the amount of required network resource. Moreover, the OLT can also keep track of the network state information, thus facilitating the network fault localization. The protection scheme feasibility and system performances are experimentally verified

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with 10 Gb/s DS and 1.25 Gb/s US data in both working and protection modes.

2 Proposed Architecture and Operation Principle

Figure 1 shows the schematic of our proposed centrally controlled self-healing WDM-PON architecture, which consisted of an OLT, a remote node (RN) and N colorless ONUs. At the OLT, multiwavelength (MW) optical carriers with a 50-GHz interval from an MLS are first fed into a Mach–Zehnder modulator (MZM) to generate the MW OCS-double sidebands. The MZM is biased at the transmission null point and driven by an RF clock at 12.5 GHz. Then the OCS-double sidebands are separated by an optical IL, which is connected to a 1×2 OS. Figure 2 depicts the optical spectra utilization of the proposed system. The red and blue lines are the spectra from the odd port and even port of the IL, respectively. The input MW optical carriers $(\lambda_1, \lambda_2 \ldots \lambda_N)$ with 50-GHz interval should be aligned with the cross points of output spectra, as indicated in Fig. 2(a). The RF clock signal for the OCS process is 12.5 GHz, thus the lower sidebands $(\lambda_{1,\mathrm{L}}, \lambda_{2,\mathrm{L}} \ldots \lambda_{N,\mathrm{L}})$ and upper sidebands $(\lambda_{1,\mathrm{U}}, \lambda_{2,\mathrm{U}} \ldots \lambda_{N,\mathrm{U}})$ can be highly separated by the IL, as illustrated in Fig. 2(b). The lower sidebands from the odd port and upper sidebands from the even port are shown in Figs. 2(c) and 2(d).

As illustrated in Fig. 1, the upper sidebands and lower sidebands are fed to port 1 and port 2 of the 1×2 OS, respectively. Port 3 of the 1×2 OS is connected to a $1 \times N$ arrayed waveguide grating (AWG). According to the state of the OS, either the upper sidebands or the lower sidebands are further demultiplexed to the corresponding wavelength channel by the $1 \times N$ AWG. In each channel at OLT, an MZM is used to modulate the respective sideband with the DS data. An optical circulator is used to separate US and DS signals and transfer the US remodulated signal to a US receiver (US-RX). The US-RX also serves as an optical monitor for the response for detecting fiber failure and generating an electrical signal to a multi-input, single-output (MISO) logic OR gate control circuit. The output of the logic OR gate control circuit is used to control the connection state

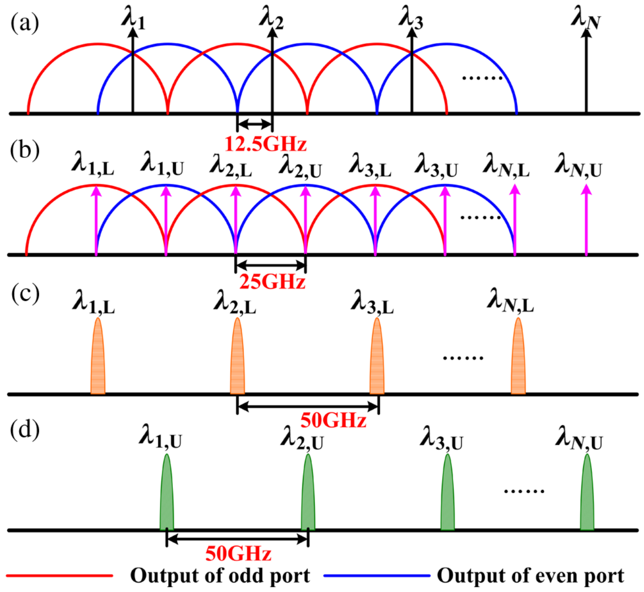

Fig. 2 Spectra of the optical carrier suppression-double sidebands used for the protection scheme. (a) Input multiwavelength optical carriers; (b) output from the Mach–Zehnder modulator; (c) odd port of the interleaver (IL); and (d) even port of the IL.

(cross or bar) of the OS. The modulated DS data in all channels are multiplexed by another $1 \times N$ AWG. Then the MW upper sideband or lower sideband signal are routed by an IL to the working FF and the protection FF, respectively, which is connected to two $1 \times \mathrm{N}$ AWGs at the RN. The two AWGs demultiplex/multiplex the DS/US upper sideband signal and lower sideband signal, respectively. These demultiplexed carriers are then transmitted to their respective designated ONUs, via two sets of DFs. At each ONU, the received DS signal is tapped off by a 3 dB 2×2 OC, where one part of the received optical power is directly detected to retrieve the DS data, while the other part is amplified and remodulated with US data via an RSOA operating in its gain-saturated regime.

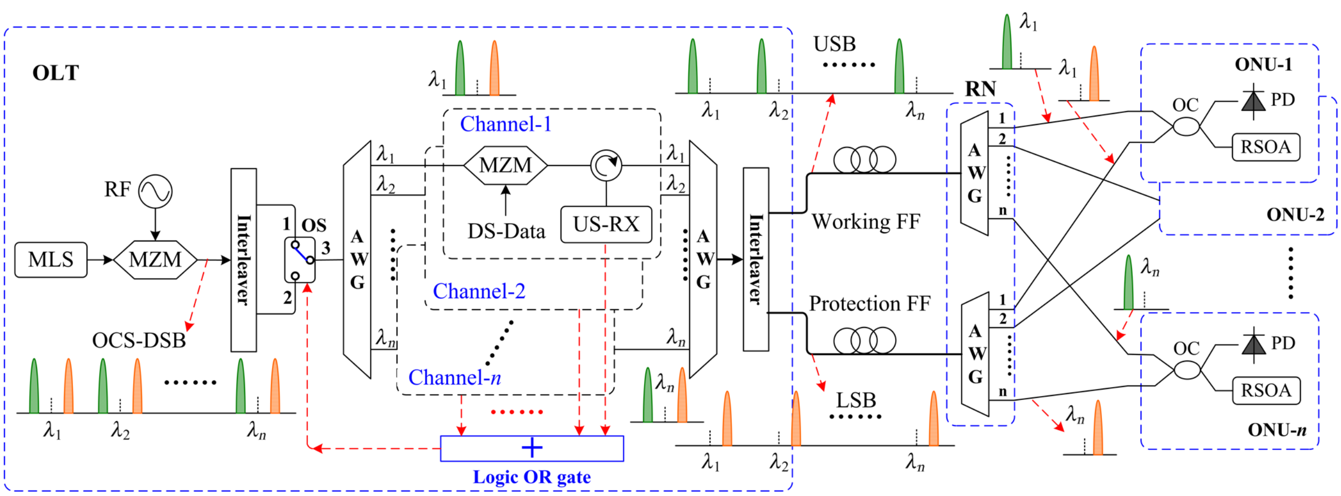

Fig. 1 Schematic diagram of the proposed cross-protection colorless wavelength division multiplexing passive optical network (WDM-PON).

Under the normal working mode, the OS is set to the ports 1 to 3 connection. Thus, the upper sideband optical carriers are modulated by the MZM in corresponding channels with the DS data and then transmitted through the working path to corresponding ONUs. In the case of any working DF failure, the corresponding US-RX will detect the loss of US signals and then an electrical trigger signal will be generated to the logic OR gate control circuit. Consequently, the output of the control circuit will trigger the OS to the ports 2 to 3 connection to setup an alternate (protection) path. Hence, the lower sideband optical carriers (instead of the upper sidebands) are modulated by the MZM in corresponding channels with the DS data and are transmitted through the protection path to the corresponding ONUs. In case an FF fails, all US-RXs simultaneously generate electrical signals to the control circuit for logic decision, whose output trigger signal will similarly change the OS's connection state. Hence, all of the bidirectional transmissions are switched from the working fibers to the backup protection fibers. In this way, the architecture can provide the centralized fast automatic protection switching function against the failures of both FF and DFs. It is worth mentioning that the proposed protection scheme can also facilitate the fiber fault localization by recording the power detection information on the US loopback signals via an optical time-domain reflectometer function module integrated in the US-RX. The US-RXs can tell if it is a DF or the FF failure in the working path. If it is a DF failure, it can also tell which DF fails and the position where the failure occurs in the DF. Hence, a fast failure restoration can be performed.

3 Experimental Setup and Results

Since a WDM-PON essentially provides a point-to-point wavelength connection between each ONU and its associated transceiver channel in the OLT, in what follows, we focus on the operation of a simplified single channel between an ONU and its associated transceiver in the OLT, specifically ONU-1 and transceiver-1 in the OLT, as any of the other channels are the same. To verify the transmission performance and the protection switching time of the proposed centrally controlled self-healing scheme in a WDM-PON, we performed a single channel experiment, as shown in Fig. 3. In the OLT, a laser diode (LD) operating at 1553.234 nm through a polarization controller was first fed into a LiNbO3 MZM, which was driven by a 12.5-GHz RF clock signal and simultaneously modulated by 10 Gb/s data with a pseudorandom bit sequence (PRBS) length of $2^{31}-1$ to generate a DS nonreturn-to-zero on–off keying (OOK) signal in the OCS-double sidebands with the extinction ratio (ER) of around 5 dB. Note that since the DS light is reused and remodulated with US data, the DS signal should have a low ER (e.g., up to 5 dB) so that the interference from the DS to the US is minimized and the error-free US transmission can be achieved, which has been experimentally verified in our previous works.[9] The generated OCS-double sidebands, with 25 GHz (0.2 nm) interval and 30-dB side mode suppression ratio, as shown in Fig. 3(a), are separated by the 25/50 GHz IL. Then the upper sidebands and lower sidebands are extracted out from the even port and odd port to port 1 and port 2 of the 1×2 OS, respectively. The 1×2 OS used in the experiment was a commercial DiCon prism switch, which has a switching speed of a few milliseconds (maximum 10 ms), a maximum insertion loss of 1 dB, and a maximum crosstalk of −70 dB. The modulated DS data are optically amplified by an erbium-doped fiber amplifier (EDFA) to compensate the DS power loss and to improve the power budget. The optical circulator was used to separate the down-/upstream signals. Then the DS data are fed into the working or protection fiber via another 25/50 GHz IL. Figures 3(b) and 3(c) show the spectra of the DS signal for upper sidebands and lower sidebands. Two 1×16 AWGs located in the RN have a channel spacing of 100 GHz (0.8 nm) and a free-spectrum range of 31 nm. The total (FF + DF) working and protection of single-mode fiber (SMF) is 20 and 25 km, respectively.

At ONU-1, a 3-dB 2×2 OC was used to power-split the DS signal equally. One part was received by an avalanche photodiode (APD) receiver, and the other part of the signals was fed into a gain-saturated RSOA, which is modulated with a set of 1.25 Gb/s $2^{31}-1$ PRBS to realize the DS data

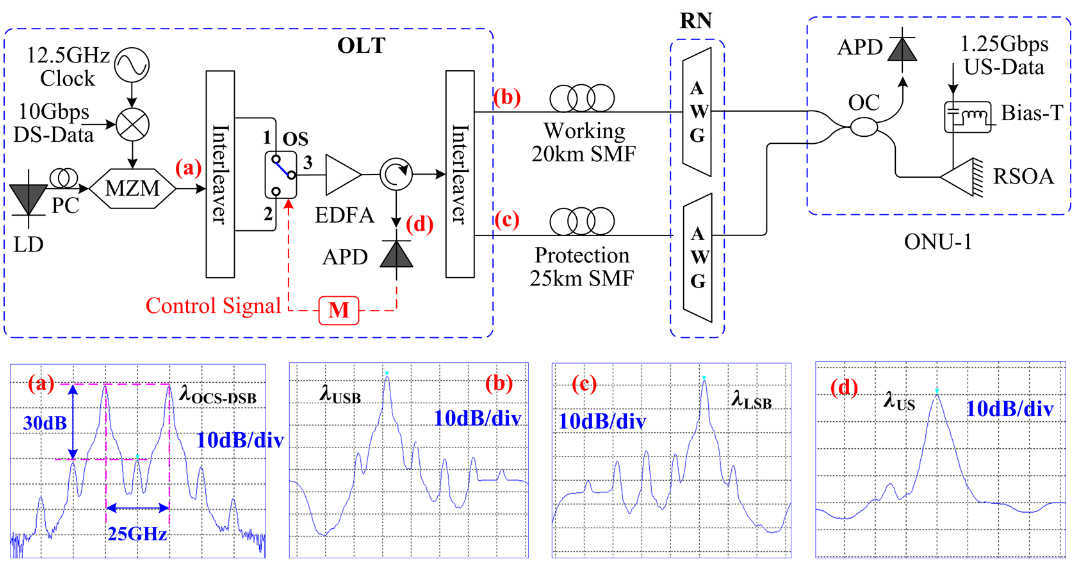

Fig. 3 Experimental setup for the proposed cross-protected colorless WDM-PON.

erasing and the US data remodulating. The uncooled RSOA used in our experiment was a multiquantum-well buried heterostructure device packaged in a transistor outlook can. The RSOA was biased at 30 mA via a bias-T circuit and the optical power injected into the RSOA was −15 dBm. At these conditions, the RSOA was saturated with an output power of 7.5 dBm (i.e., optical gain = 22.5 dB), and its 3-dB modulation bandwidth was measured to be 1.5 GHz. The remodulated US data are transmitted through the US link to the OLT, where it is directed by an optical circulator and directly detected by an APD receiver, as shown in Fig. 3(d) for real-time monitoring of a power outage. In the initial working mode, the OS was assumed to link port-1 to port-3. Thus, the DS and US upper sidebands traversed the working path in a round trip. We intentionally disconnected the DF link to simulate the fiber cut scenario, which was identified by a drastic drop in US signal power. With the proposed protection scheme, the control unit reconfigured the OS state quickly. The DS and US traffic in all channels were switched automatically to the alternate protection path, i.e., the OS was a port-2 to port-3 connection, and lower sidebands contributed.

Figures 4 and 5 show the measured bit error rate (BER) curves and eye diagram for the 10-Gbps DS signal and the 1.25-Gbps US signal with the normal working path (20 km) and protection path (25 km), respectively. In these BER measurements, the DS ER is set at 5 dB to achieve error-free US transmission, and the injected optical power to the RSOA was maintained at −15 dBm. Under these conditions, the DS receiver sensitivities with the working and protection path are −30.4 and −29.8 dBm at BER of 10^{-9}, as shown in Fig. 4. Compared with the DS back-to-back (BTB) case, the power penalties for the protection and working mode are about 1.2 and 1.8 dB, which could be attributed to the fiber chromatic dispersion and the backscattering noise. In the case of US transmission, Fig. 5 shows that the receiver sensitivities of the US signals for the working and the protection mode are −34.6 and −33.4 dBm at BER of 10^{-9}, respectively. There is about a 1.2 and 2 dB power penalty at the BER of 10^{-9} between the working and the protection mode and the BTB transmission for US signals due to the backscattering noise. The eye patterns

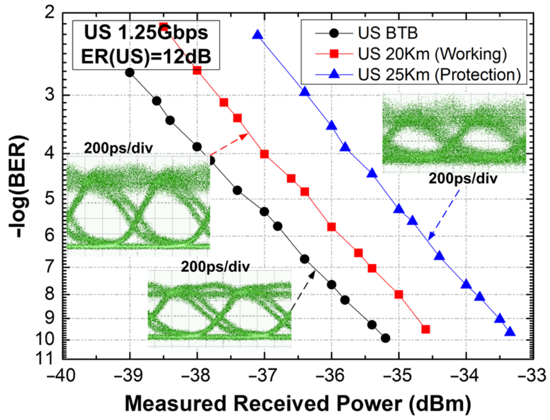

Fig. 5 Measured BER of the 1.25 Gbit/s upstream (US) signals both in the working and protection path at 1553.234 nm. Insets show the optical eye patterns when the US ER is 12 dB.

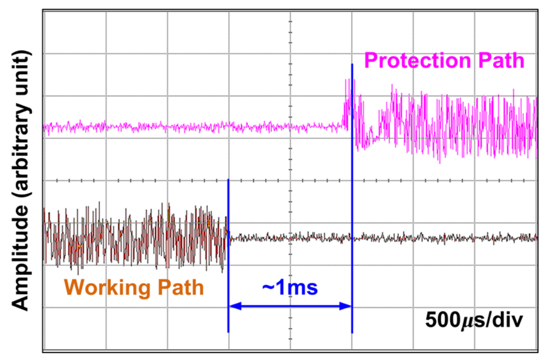

Fig. 6 Measured switching time during traffic restoration.

for the DS and US signals with 5 and 12 dB ER are also demonstrated in the insets of Figs. 4 and 5. We also measured the protection switch time for the DS loopback signal. The upper trace represented the DS signal in the protection path, whereas the lower trace was for the case with a working path. As shown in Fig. 6, the protection switch time was around 1 ms in the case of the simulated fiber cut, which is mainly determined by the switching response of the commercial DiCon 2×2 prism switch used in the experiment.

To show the network scalability of the self-healing WDM-PON, a power budget analysis was performed in Table 1. We assume that the DS EDFA has a gain of 20 dB, the output power from a LD is about 5 dBm, the RSOA has a saturated output power of 7.5 dBm when it is biased at 30 mA, and the injected optical power is equal to or greater than −15 dBm. The total power losses include a 5-dB insertion loss induced by the MZM, an insert loss of 0.8 dB for the optical circulator, an insert loss of 1 dB for the optical IL, an insert loss of 5 dB for the $1 \times N$ AWG, an insert loss of 1 dB for the 1×2 OS, a 6-dB transmission loss for 25-km SMF and a 3-dB loss of the 2×2 OC. Thus, for the DS transmission, the power margin of 27.3 dB could be obtained with the consideration of receiver sensitivity of around −30.1 dBm. The power margin of 18.7 dB was also obtained with the average US sensitivity of −34 dBm. These

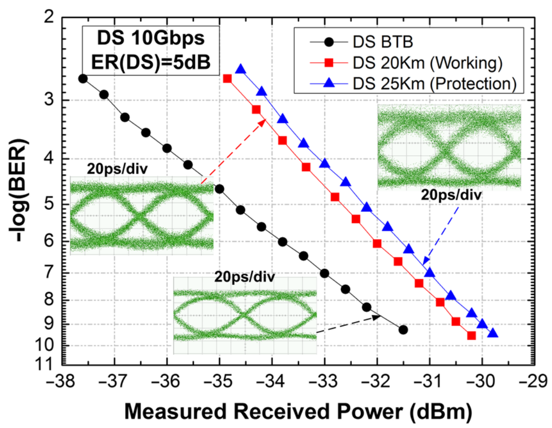

Fig. 4 Measured bit error rate (BER) of the 10 Gbit/s downstream (DS) signals at 1553.234 nm for a working path and protection path. Insets show the optical eye patterns when the DS extinction ratio (ER) is 5 dB.

Table 1 Power margin calculation for downstream (DS) and upstream (US) data.

Element insertion loss	DS	US
Laser output power at OLT (dBm)	4	—
Erbium-doped fiber amplifier gain (dB)	20	—
Injected power into RSOA (dBm)	—	≥ -15
RSOA saturated output power (dBm)	—	7.5
Mach–Zehnder modulator loss (dB)	5	—
Circulator insertion loss (dB)	0.8	0.8
Interleaver insertion loss (dB)	1×2[a]	1×2[a]
Arrayed waveguide grating insertion loss (dB)	5×2[a]	5×2[a]
Optical switch insertion loss (dB)	1	1
20/25 km (FF + DF) single-mode fiber loss (dB)	5	6
Optical couplers insertion loss at optical network units (dB)	3	3
Insertion loss (dB)	26.8	22.8
Average[b] receiver sensitivity (dBm)	−30.1	−34
Power margin (dB)	27.3	18.7

Note: RSOA, reflective semiconductor optical amplifier.
[a]"×2" means the optical signal experiences the loss twice.
[b]An average value is taken between the working and protection modes.

higher power margins indicate the feasibility of the larger transmission scope in the proposed WDM-PON.

4 Conclusions

In this paper, we have proposed and experimentally demonstrated a centrally controlled self-healing scheme for colorless WDM-PONs with 10-Gb/s DS and 1.25-Gb/s US transmissions in both working and protection modes. By applying the OCS technique to generate the double sidebands, which are routed on two alternate paths, only one OS is required at the OLT. The OS is centrally controlled by the logic OR gate control circuit in the OLT upon monitoring of a power outage on the working path. The survivable protection architecture can protect against both FF and DF failures. Moreover, the OLT can also record the network state information, thus facilitating the network fault recovery. The proposed architecture not only simplifies the ONU design, but also significantly reduces network complexity.

Acknowledgments

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