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## **C + L band wavelength division multiplexing access network with distributed-controlled protection architecture**

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**Abstract.** In this work, we propose and experimentally demonstrate a novel distributed-controlled protection architecture for automatic and fast network restoration in wavelength division multiplexing-passive optical network (WDM-PON). The proposed scheme can support both C and L bands. Besides, duplication of network equipments, such as optical networking unit (ONU) or optical line terminal, is not required. In this distributed-controlled system, each ONU can always keep track of the network status. Hence, this can facilitate the network manage by removing the work loads from the central office. Besides, the proposed scheme can tolerate simultaneous fiber cuts in the feeder and distributed fibers.

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## 1 Introduction

The wavelength division multiplexing-passive optical network (WDM-PON) is a promising candidate to deliver high capacity broadband services to business and residential subscribers.<sup>1</sup> As end-users are demanding faster and higher quality broadband services, reliable WDM-PON are highly desirable in the near future. However, when a fiber cut occurs in the distributed fiber [fiber between the remote node (RN) and the optical network unit (ONU)] or in the feeder fiber [fiber between the central office (CO) and the RN], the ONU will become unreachable from the CO, leading to data loss. Therefore fault management is one of the important issues to improve the network reliability. Recently, several network protection architectures have been proposed.<sup>2-7</sup> They usually require duplicated network resources, such as ONU and optical line terminal (OLT) for the network protection. References 8 and 9 require active electrical control and management at the RN and at the OLT in the CO, respectively, for optical path protection against fiber fault. Reference 10 requires wavelength tunable laser source at each ONU. The tunable laser can simultaneously provide an upstream signal and optical path restoration using wavelength switching.

In this work, we propose and experimentally demonstrate a novel distributed-controlled protection architecture for the WDM-PONs. Our proposed scheme can also support both C- and L-bands. It can also tolerate simultaneous fiber cuts in the feeder and distributed fibers. In the proposed scheme, each ONU can keep track of the network status, and active control in the RN and OLT is not required when compared with Refs. 8 and 9. Hence, this can facilitate the network manage by removing the work loads from the OLT. Besides, tunable laser sources for optical path restoration are not required when compared with Ref. 10.

The paper is organized as follows: in Sec. 2, the network protection architecture is proposed. The operation principle for protection in feeder or distribution fibers is discussed. In

Sec. 3, the experimental results showing the performance or the protection scheme are provided. A comprehensive comparison of our proposed scheme with other recently reported schemes in the literatures are also presented. Finally, a conclusion is given in Sec. 4.

## 2 Architecture

To improve the bandwidth utilization of the optical fiber, both C- and L-bands will be used in the proposed WDM-PON, as shown in Fig. 1. Figure 2 shows the network architecture of the protection scheme. In the CO, there are two line terminals (LTs) for the C-band (LT<sub>C</sub>) and L-band (LT<sub>L</sub>), respectively. In each LT, the three-port optical circulator (OC) is used to separate the upstream and downstream signals. The downstream signal from the LT is divided into two paths by a 1×2 optical coupler (CP) and transmitted into the normal fiber (path 1) and protection fiber (paths 1'). The RN consists of two 1×2 C-/L-band WDM couplers (WC) and two 1×N arrayed waveguide gratings (AWGs). The WC inside the RN can combine the C- and L-band optical downstream signals sent from LT<sub>C</sub> and LT<sub>L</sub>, respectively. The common port of the WC is connected to the AWG. Although the upper AWG is used to connect the ONUs in C-band while the lower AWG is used to connect the ONUs in L-band, the two AWGs can operate in C + L band with the same spectral periodicity property.

Two ONUs (ONU<sub>Ci</sub> and ONU<sub>Li</sub>,  $i = 1, 2, 3, \dots, N$ ) are assigned to act as a group, one operates in C-band and the other operates in L-band. The proposed wavelength assignments for the downstream and upstream channels are shown in Fig. 3. The downstream wavelengths (C<sub>di</sub>, L<sub>di</sub>) and the upstream wavelengths (C<sub>ui</sub>, L<sub>ui</sub>) in the  $i$ 'th ONU group (for  $i = 1, 2, 3, \dots, N$ ) are assigned with the wavelength separation by one free spectral range of the AWG, as illustrated in Fig. 3. This means that one port of the AWG can support the four wavelengths simultaneously due to the spectral periodicity property.

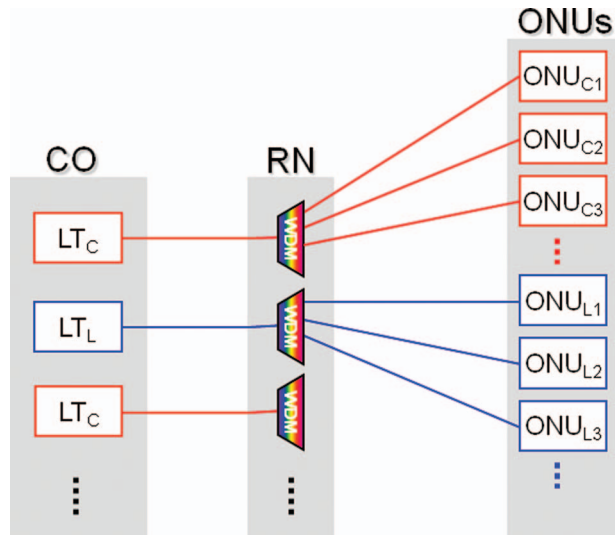


Fig. 1 Schematic of the proposed C + L band WDM-PON.

Inside each ONU, a C-band optical coupler (CCP) or L-band optical coupler (LCP), a  $1 \times 1$  optical switch (OS), and a C + L band  $2 \times 2$  CP are used in front of the transmitter and the receiver (Rx), as shown in the inset of Fig. 2. The CCP in the C-band ONU can remove the L-band downstream signal  $L_{di}$ , while the LCP in the L-band ONU can remove the C-band downstream signal  $C_{di}$ .

In the normal state (there is no fiber cut), the two OSs in each ONU pair are "OFF." The OS is controlled by medium access control (MAC) layer. The downstream and upstream traffics are transmitting in fiber paths 1 and 2 while the signals in fiber paths 1' and 2' are blocked by the OS in each ONU in the normal state.

When a fiber cut occurs on the distributed fiber between the RN and  $ONU_{C1}$  as shown in Fig. 4, the data traffic between the CO and  $ONU_{C1}$  will be disconnected. Since the

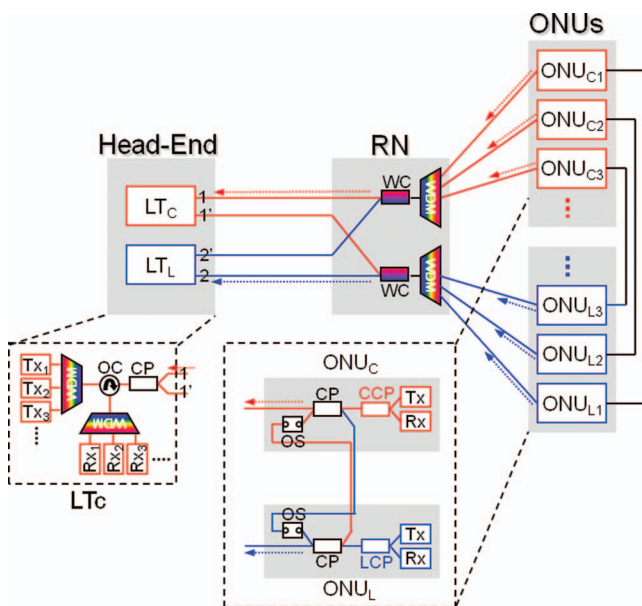


Fig. 2 The proposed distributed-controlled protection WDM-PON architecture.

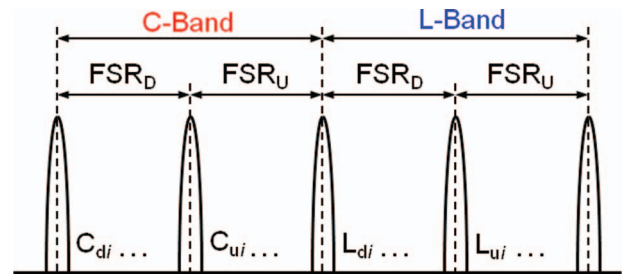


Fig. 3 The wavelength assignment plan for the upstream and downstream signals.

Rx of the  $ONU_{C1}$  cannot receive the downstream signal, then the OS will be switched "ON" by the MAC. Hence the  $ONU_{C1}$  reconnect both the downstream and upstream signals through the partner  $ONU_{L1}$  via the protecting fiber on path 1', as shown in the inset of Fig. 4. Without the loss of generality, the same automatic re-routing mechanism can also be applied to the  $ONU_{L1}$  while the fiber cut is located in the distributed fiber connecting the L-band ONUs.

When a fiber cut occurs in the feeder fiber path 1 between the RN and CO, as shown in Fig. 5. All C-band  $ONU_C$ s cannot detect the downstream signals from CO. Thus, the OS in each  $ONU_C$  will switch "ON" for signal reconnection via the corresponding  $ONU_L$ s through the protection fiber on path 1'. Without the loss of generality, the same automatic re-routing mechanism can also be applied when the fiber cut occurs in feeder fiber path 2 for the network restoration. It is also worth mentioning that the proposed scheme can tolerate simultaneous fiber cuts in both the feeder and distributed fibers. When fiber cuts occur in both the feeder and distributed fibers, all the C-band  $ONU_C$ s cannot detect the downstream signals from CO. Thus, the OS in each  $ONU_C$ s will switch "ON" for signal reconnection via the corresponding  $ONU_L$ s through the protection fiber on path 1'.

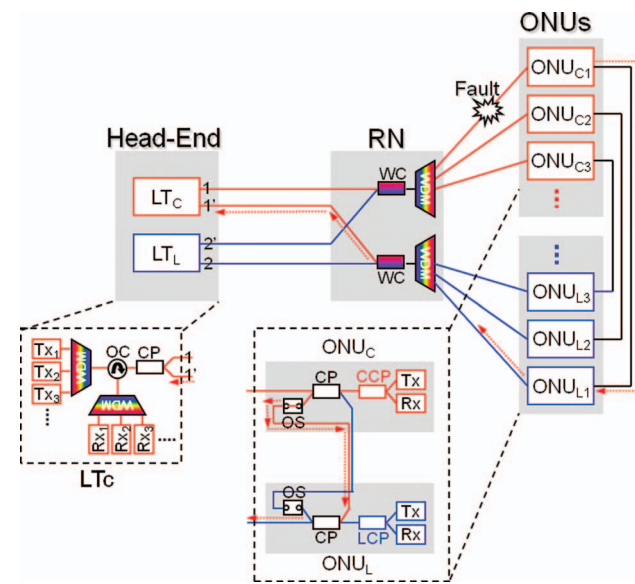
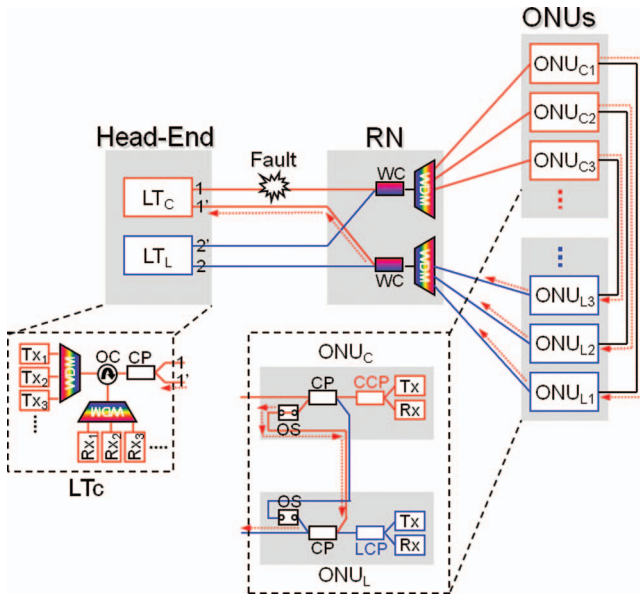


Fig. 4 A fiber cut occurs at the distributed fiber between the RN and the  $ONU_{C1}$ , and the network restoration path.



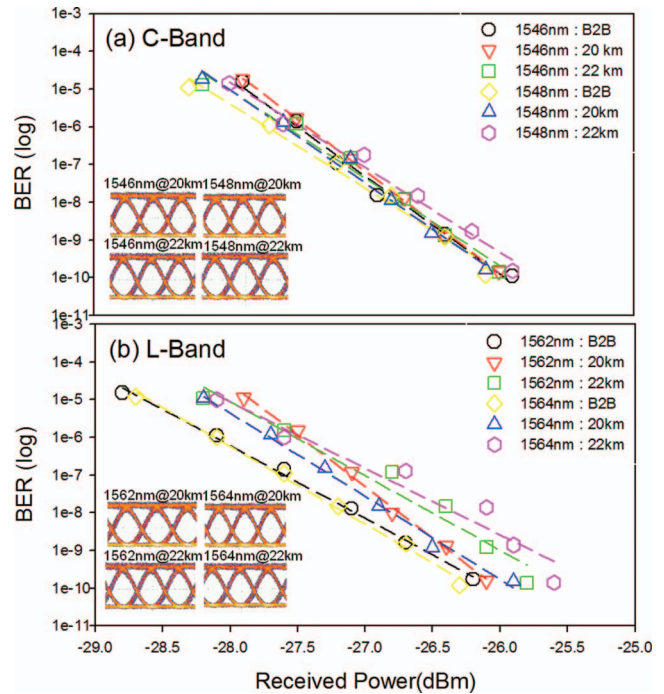
**Fig. 5** A fiber cut occurs at the feeder fiber between the CO and the RN, and the network restoration path.

### 3 Experiments and Discussion

To investigate the performance of the proposed WDM-PON, we selected four wavelengths to emulate the downstream and upstream wavelengths for  $ONU_{C1}$  and  $ONU_{L1}$ . In this experiment, the wavelengths of  $C_{d1}$ ,  $C_{u1}$ ,  $L_{d1}$ , and  $L_{u1}$  are 1546.0, 1548.0, 1562.0, and 1564.0 nm. The total length of the feeder and distributed fibers is 20 km. The fiber connecting the ONU pair is 2 km. All the fibers are standard single mode fiber (SSMF). Both the downstream and upstream signals are modulated at 10 Gb/s nonreturn-to-zero format with  $2^{31}$  to 1 pseudorandom binary sequence data via a LiNbO<sub>3</sub> Mach-Zehnder modulator. Optical preamplified Rx using erbium-doped fiber amplifier (EDFA) was used for the bit error rate (BER) analysis. Figures 6(a) and 6(b) show the BER performances of downstream and upstream signals between the CO and the  $ONU_{C1}$  back-to-back without fiber transmission, in the normal state [20 km single mode fiber (SMF) transmission] and the protection state (22 km SMF transmission). Figure 6(a) shows the measured power penalties between CO and  $ONU_{C1}$  are less than 0.5 dB at a BER of  $10^{-9}$  without and with fault cut. Figure 6(b) also shows the measured power penalties are about 0.8 dB at a BER of  $10^{-9}$ . The larger penalty of Fig. 6(b) is due to the amplification limitation of the EDFA used in the experiment. Moreover, the insets of Fig. 6(a) are the measured corresponding eye diagrams of downstream and upstream signals at the BER of  $10^{-9}$  with and without protecting operation after 20 and 22 km fiber transmissions, respectively. These measured eyes are wide opening and clear.

Besides, the automatic switching time was also measured, and the switching time of the OS is about 10 ms as shown in Fig. 7. By considering the insertion losses of the OS ( $\sim 0.5$  dB), an AWG ( $\sim 5$  dB), two CPs ( $\sim 6$  dB), a WC ( $< 1$  dB), an OC ( $< 0.5$  dB), and the 22 km SSMF (0.2 dB/km), the total loss budget is about 18 dB.

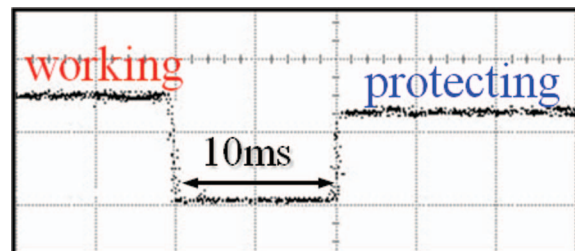
In the proposed scheme, each ONU can always keep track of the network status and control its own OS for network restoration. Hence this is a distributed-controlled system.



**Fig. 6** BER performances of downstream and upstream traffic (a) between CO and  $ONU_{C1}$  (C-band) and (b) between CO and  $ONU_{L1}$  (L-band) with and without fault protection, respectively. The insets of (a) are measured corresponding eye diagrams for downstream and upstream signals with and without protection, respectively.

This can facilitate the network manage by removing the work loads from the CO. Besides, the proposed scheme can tolerate simultaneous fiber cuts in the feeder and distributed fibers. In the experiment, we only demonstrated four wavelengths. In practice, the proposed scheme can support 80 WDM wavelengths using both C + L bands (40 wavelengths in the C-band and 40 wavelengths in the L-band). The number of supported wavelengths can be further increased if dense WDM (DWDM) is used.

We have experimentally compared our proposed scheme with other recently reported schemes in the literatures as shown in Table 1. The yellow shaded boxes are the advantages provided by the scheme. The experimental results showed that our proposed scheme has a higher power penalty between working and protection states ( $\sim 0.8$  dB), while other schemes in Refs. 9 and 10 and in Ref. 8 have about 0.5 dB and negligible power penalty, respectively. Our proposed scheme also has a longer switching time between the two states (10 ms), while other schemes<sup>8-10</sup> have the switching time from 1 to 8 ms. The switching time can be improved by



**Fig. 7** The switching time of optical switch on each ONU.

**Table 1** Comparison of our proposed scheme with other recently reported schemes.

	Protection of both feeder and distribution fibers	Active control between CO and ONU	Power penalty between working and protection states	Switching time (ms)	Duplication of ONU and OLT for protection	Requirement of tunable laser in ONU	Operation Bandwidth	Additional cost
Proposal by KAIST, et al. (Ref. 8)	Yes	Yes	negligible	1	No	No	C-band	Optical switches and RN control unit
Proposal by CUHK (Ref. 9)	No	No	~0.5 dB	5	No	No	C-band	Mach-Zehnder modulator with 40 GHz clock source at the CO
Proposal by Georgia Tech. et al. (Ref. 10)	Yes	No	~0.5 dB	8	No	Yes	C-band	High speed tunable laser at each ONU
Our proposed scheme	Yes	No	~0.8 dB	10	No	No	C-plus L-bands	Optical switches, couplers and fiber paths

using a better optical switch. Our scheme can protect both feeder and distribution fibers, and it does not require active control between the CO and ONU. We can also see that the additional cost of our proposed scheme is due to the optical switches, fiber couplers, and fiber paths connecting adjacent ONUs. We think that this additional cost is worthy for the protection. We also believe that the cost could be lower for the scheme requiring a Mach-Zehnder modulator and 40 GHz clock source,<sup>9</sup> and the scheme using high speed tunable laser at each ONU.<sup>10</sup> Moreover, other protection schemes<sup>8-10</sup> could only be employed in C-band for WDM operation. For example, 40 wavelength channels can be used in the C-band (1530 to 1560 nm) for WDM transmission while the channel spacing is 100 GHz (0.8 nm). Here, our proposed PON architecture can also support both C- to L-bands (1530 to 1600 nm) for providing twice the capacity when compared with Refs. 8-10.

#### 4 Conclusion

We proposed and experimentally demonstrated a novel distributed-controlled protection architecture for automatic and fast traffic restoration against fiber cut in WDM-PONs. Duplication of network equipments, such as ONU or OLT, is not required in the proposed scheme. Power penalties of <1 dB at BER of  $10^{-9}$  was measured in the proposed protection scheme. The switching time between normal and protection states was about 10 ms. In this distributed-controlled system, each ONU can always keep track of the network status, and control its own OS for network restoration. Hence this can facilitate the network manage by removing the work loads from the CO. Besides, the proposed scheme can tolerate simultaneous fiber cuts in the feeder and distributed fibers.

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