Abstract—A novel, reliable wavelength-division-multiplexed passive optical network (WDM-PON) with self-protection capability is proposed. By utilizing the routing characteristics of $N \times N$ arrayed waveguide grating, the proposed architecture can provide automatic protection against any fiber cut between central office and optical network unit (ONU). Compared with the conventional schemes, this scheme adopts colorless ONUs, thus leading to a decrease in the costs of operation, administration, and maintenance, as well as the production cost. Without the performance degradation, the proposed WDM-PON scheme can offer a reliable network service. In the experiment, the protection performance was demonstrated in the carrier-distributed 1.25-Gb/s WDM transmission over 20-km single-mode fiber.

Index Terms—Arrayed waveguide grating (AWG), self-protection, wavelength-division-multiplexed passive optical network (WDM-PON).

I. INTRODUCTION

TO DATE, with the explosive growth of end user demand for higher bandwidth, various types of passive optical networks (PONs) have been proposed. PON can be roughly divided into two categories such as time-division-multiplexing (TDM) and wavelength-division-multiplexing (WDM) methods [1], [2]. Compared with TDM-PONs, WDM-PON systems allocate a separate wavelength to each subscriber, enabling the delivery of dedicated bandwidth per optical network unit (ONU). Moreover, this virtual point-to-point connection enables a large guaranteed bandwidth, protocol transparency, high quality of service, excellent security, bit-rate independence, and easy upgradeability. Especially, recent good progress on athermal arrayed waveguide grating (AWG) and cost-effective colorless ONUs [3] has empowered WDM-PON as an optimum solution for the access network. However, fiber link failure from the optical line terminal (OLT) to the ONU leads to the enormous loss of data. Thus, fault monitoring [4], [5] and network protection [6]–[12] are crucial issues in network operators for reliable network. To date, many methods have been proposed for network protection. In the ITU-T recommendation on PONs (G.983.1), duplicated network resources such as fiber links or ONUs are required. In [6]–[8], the periodic and cyclic properties of AWGs are used to interconnect two adjacent ONUs by a piece of fiber. In [9], a wavelength-shifted protection scheme is reported. In [10], affected traffic can be rerouted via the adjacent RN.

Recently, we have proposed a simple colorless WDM-PON network architecture by use of $2 \times N$ AWGs [11] to provide protection against fiber link failure between the OLT and RN. However, it can provide protection function only in the fiber link between CO and RN.

In this letter, we propose and demonstrate a new protection scheme for colorless WDM-PON. This architecture utilizes the periodic and cyclic properties of $N \times N$ AWG for protection against both feeder fiber and distribution fiber link failures. Compared with previous schemes [5]–[9], this architecture is implemented by duplicating only fibers without any other transmitters, receivers, or RNs, which largely simplifies the network and reduces the cost. The feasibility of the proposed scheme is experimentally verified using the colorless WDM-PON.

II. ARCHITECTURE AND OPERATING PRINCIPLE

Fig. 1(a) shows our proposed bidirectional WDM-PON architecture with $N - 1$ colorless ONUs. To implement bidirectional transmission, it uses two different wavelength bands...
for upstream and downstream signals. Fig. 1(b) shows the wavelength assignment plan. The WDM-PON uses $L$- and $C$-bands for the downstream and upstream signals, respectively. Two wavelength bands are separated by the free spectral range (FSR) of the AWG with a cyclic property. $C$-band and $L$-band broadband light sources (BLS), supplying unmodulated optical carriers for ONUs and CO transmitters, respectively, are located at the central office (CO). The $L$-band BLS is coupled to $C/L$ WDM combiner, followed by a $1 	imes N$ AWG, which demultiplexes it. The demultiplexed BLSs are injected into the Fabry–Pérot laser diodes (FP-LDs) and are modulated with downstream data. Then they are multiplexed by the $1 	imes N$ AWG, combined with $C$-band BLS by the $2 	imes 2$ couplers, which connects the RN via a pair of working and protection feeder fibers as shown in Fig. 1(a). Thus, identical downstream and $C$-band BLS signals are carried to the RN through both working and protection $C$-band downstream fibers. The RN consists of $N 	imes N$ AWG which has the same FSR as $1 	imes N$ AWG at CO.

At the RN, feeder fibers $F_I$ and $F_{II}$ are connected to the two input ports of $N_{th}$, $N_{th}$ of the $N 	imes N$ AWG, respectively.

There are also two distribution fibers (working ($D_{II,i}$) and protection ($D_{II,i}$) fibers) connecting RN and each ONU$_i$. As illustrated in Fig. 1(a), each ONU consists of a power monitor (M), optical switch (OS), and transceiver. Under normal operation, each switch is connected to the corresponding working distribution fiber. The corresponding $L$-band downstream signal ($L_i$) and $C$-band carrier ($C_i$) are transmitted to ONU$_i$ via the working distribution fiber $D_{I,i}$. At ONU$_i$, the downstream signal and upstream carrier are separated by the $C/L$ WDM couplers, and then downstream signal arrives at the receiver, while the optical carrier is amplified and modulated by the transmitter and sent back to the CO via the same paths.

Without loss of generality, the working distribution fiber $D_{I,i}$ is considered to be cut as an example to illustrate the protection. In case of distribution fiber $D_{I,i}$ cut, the power monitor ($M_i$) in ONU$_i$ detects the loss of signal, and the control unit triggers the OS to reroute the optical signals to the protection path $D_{II,i}$ as shown in Fig. 1(a). As a result, the affected traffic can be restored promptly without disturbance in any other existing traffic. On the other hand, in case of working feeder fiber ($F_I$) failure, every optical switch on ONUs simultaneously reroutes the optical signals to protection distribution fibers. Thus, this architecture can offer the automatic protection function against the failures of both feeder and distribution fibers by duplicating only the fibers without other redundant transceivers.

III. EXPERIMENTAL RESULTS

We have experimentally demonstrated the proposed self-protecting WDM-PON using the setup shown in Fig. 2. Low-cost FP-LDs were used as the transmitters at the OLT and two ONUs. Here, only the FP-LDs connecting the first port of AWGs are directly modulated at 1.25 Gb/s with $2^{31} - 1$ pseudorandom binary sequence data. We used $C$- and $L$-band erbium-doped fiber amplifiers for seed lights for colorless ONU and CO-transmitter implementation, respectively. We used a $16 	imes 16$ cyclic AWG with 100-GHz channel spacing and an FSR of 31 nm for RN. The AWG at CO has the same channel spacing and FSR as RN-AWG. The feeder fiber link between CO and RN was about 15 km while distribution fibers were 5 km long. The distribution fiber link failure was simulated by an optical switch OS as shown in the Fig. 2.

We measured the switching time, i.e., the protection time in case of fiber cut. The result is shown in Fig. 3. The upper trace represents the monitor signal from which we can detect the working fiber failure. The second and third traces in Fig. 3 represent the optical power of the downstream and upstream signals received at the ONU and OLT sides, respectively. From both traces, the switching time from the working to protection fiber was measured to be about 4 ms which is mainly determined by the switching performances of the optomechanical switches which we used.

We also measured the bit-error-rate (BER) performances of the upstream and downstream signals between the ONU1 and TRx1. First, the eye diagram analysis at 1.25 Gb/s was performed to characterize the data transmission performance of directly modulated FP-LD with spectrum-sliced ASE injection. As seen in Fig. 4, wide opened eye patterns can be obtained for both normal and protection states. Fig. 5 shows the measured BER results of the downstream and upstream signals for the working and protection states. For the upstream case, the
measured receiver sensitivities at BER of \(10^{-10}\) were around \(-25.5\) dBm in both normal state and protection state. In the downstream case, the BER performance was almost the same. In all cases, the power penalty introduced by the protection process was negligible.

We also conducted an experiment to demonstrate the feasibility of the proposed scheme capable of protecting feeder fiber failure. The working feeder fiber between the CO and the RN was intentionally disconnected by an optical switch similarly to the distribution fiber failure experiment. After then, we measured the protection switching time and BER curves. The results were almost the same to the data shown in Figs. 3–5. This was attributed to the fact that only the fiber fault location was different and all-optical switches at ONUs were switched simultaneously.

IV. CONCLUSION

We have proposed a novel protection architecture for bidirectional WDM-PON with colorless ONUs. By incorporating \(N \times N\) AWG and optical switches, and by duplicating only fibers without any other components, it can provide self-protection capabilities against not only the feeder fiber but also the distribution fiber failures. Also, the proposed architecture was experimentally demonstrated using colorless ONUs with centralized light sources at a 1.25-Gb/s transmission speed. The results showed that the protection could be achieved within 4 ms without any power penalty. The proposed WDM-PON with features like self-protection against both feeder fiber and distribution fiber cuts may offer reliable network for service providers. Moreover, it is cost-effective due to its colorless ONUs and no redundant network equipment.

REFERENCES