All-Passive Optical Fiber Sensor Network With Self-Healing Functionality

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Ching-Hung Chang
Dong-Yi Lu
Wei-Hung Lin

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All-Passive Optical Fiber Sensor Network With Self-Healing Functionality

Ching-Hung Chang®, Dong-Yi Lu, and Wei-Hung Lin

Department of Electrical Engineering, National Chiayi University, Chiayi 60004, Taiwan

Abstract: An all-passive optical fiber sensor network is proposed based on a novel single-line bidirectional optical add-drop multiplexer (SBOADM). By reasonably employing fiber Bragg gratings and optical circulators to compose the self-developed SBOADM, single-line bidirectional transmission can be easily achieved by the SBOADM without the assistance of a power supply or optical switch. Experimental results prove that when optical signals are fed into the proposed SBOADM in clockwise or counterclockwise direction, the insertion loss of the dropped optical signals is roughly 3.7 dB or 4.5 dB, respectively, and the attenuation of each added signal is about 3.6 dB. When the SBOADM is employed to bridge a hybrid tree-based and ring-based optical fiber sensor network, self-healing functionality can be easily embedded into the network. Once an interruption occurs in the network, the only thing that the system maintainer needs to do is to adjust one optical switch pre-installed in the remote node of the sensor network. Simulation results show that the maximum power penalty caused by the self-healing function is roughly 6 dB. That is to say, the proposal can easily overcome any one fiber-link failure without adjusting the network deploying setting or employing complex control management.

Index Terms: Fiber sensor network, fiber Bragg grating, optical add-drop multiplexer (OADM), self healing.

1. Introduction

In Recent years, the application of optical fiber sensing architecture has arisen to remotely detect the characteristics of multiple objects in temperature, humidity, pressure, density, etc. [1]–[10]. The fiber Bragg grating (FBG) sensor, in particular, is widely employed to sense strain, temperature or pressure changes by monitoring the shifting of the reflected optical carrier in the wavelength. The FBG-based sensor systems have many advantages, such as electromagnetic interference immunity, lightweight, compact size, easy fabrication, broad wavelength-tunability, excellent multiplexing capability, etc. Numbers of large-scale FBG sensor networks have been experimentally demonstrated based on time-division multiplexing (TDM), wavelength-division multiplexing (WDM) and spatial- division multiplexing (SDM) techniques [11]–[21]. Nevertheless, as the amount of sensing information is increased, maintaining the resilience of optical fiber sensor networks becomes a challenge because the probability of failure in connecting fibers is increased and the amount of affected sensing traffic is generally greater when a fiber failure occurs. Research on the network
All-Passive Optical Fiber Sensor Network With Self-Healing Protection

In literature, two types of self-protection schemes have been proposed. The first type of method is to distribute FBG sensors in different sections and then, employ multiple SWs in each remote node (RN) to bridge the optical sensing signals among the FBG sensors and the central office (CO) [1]–[8]. To guard against fiber faults, the status of the SWs in each RN can be adjusted to reconfigure the sensing pathway. Numbers of architectures, including star-ring, star-ring-bus, delta-star and mesh-topology, have been published [1]–[8]. However, a large amount of SWs are needed to implement the self-protection ability. It is difficult to properly control and adjust the status of SWs in each RN and to provide power for them because the SWs are placed in the RNs rather than in the CO, so the complexity and cost of the fiber sensor network are increased significantly. In parallel, the second type of self-protection scheme is to construct an optical fiber sensor network based on optical splitters [9]–[10]. Based on the optical splitting function of an optical coupler, each FBG sensor is assigned a backup link to prevent the impact of fiber faults. One benefit from the passive characteristic of the employed optical coupler is that no power supplier is required in the second type of self-protection scheme. Nevertheless, the power budget in such sensor architectures is quite low because the optical sensing signals will go through large amounts of optical splitters during run trip transmission. In both types of self-protection schemes mentioned above, their routing schemes of the optical sensing signals do not completely utilize the benefit of the WDM technique, so the end-to-end transmission attenuations are significant.

To improve the disadvantages, such as significant transmission loss, complicated reconfiguration processes and the prerequisite power supply of both schemes above, an optical fiber sensor network with self-protection functionality based on self-composed single-line bidirectional optical add-drop multiplexers (SBOADMs) is proposed. Except for utilizing an SW and an optical splitter as an RN to bridge the CO and the sensor networks, all the other components in the sensor network, including the SBOADMs, are passive devices, so it is unnecessary to supply extra electrical power or to send out reconfiguration process signals to control the SBOADMs. Based on the novel self-developed SBOADM structure, whatever optical sensing signals are injected into the SBOADM in either a clockwise (CW) or counterclockwise (CCW) direction, the specific optical carriers can always be dropped into the connected FBG sub-sensor network and the reflected optical signals can be added and sent back to the CO along the reverse transmission direction of the downstream routing-path. When we utilize ring topology to bridge the SBOADM and FBG sub-sensor networks and to bridge the SBOADMs and the CO, the optical detection signals generated from the CO can be transmitted in either CW or CCW directions of the ring-structure network to eliminate the impact of any one fiber link failure. Except for one RN, no costly SW and highly attenuated optical splitter are utilized to reconstruct the optical routing pathway, so transmission loss can be significantly reduced.

2. Operation Principle and Experimental Demonstrating of the Proposed SBOADM

In this paper, a novel SBOADM is proposed and employed to develop an all-passive optical fiber sensor network with self-healing functionality. Traditionally, an optical network with an OADM-composed ring-topology has a potential ability to avoid fiber link failure by delivering the downstream signal from CW and CCW directions of the optical ring. Nevertheless, a traditional OADM, constructed of two optical circulators (OCs) and an FBG, can only bridge the downstream and upstream signals along a unidirectional pathway that is either a CW or CCW direction of the optical fiber ring. In order to support bidirectional transmissions, J. J. O. Pires [19] developed a 2-fiber-based bidirectional OADM (BOADM) composed of two 2 × 2 SWs, two optical amplifiers and two traditional OADMs. Such a BOADM can bridge optical network units (ONUs) to a ring-topology network by two parallel fiber rings. When a breakpoint happens in a fiber-ring, the SWs inside the BOADM can help to bypass the breakpoint by directing the optical signal to the other backup fiber ring. The network protection ability will be ensured. The main disadvantage of such a BOADM is the requirement of
It is important to notice that previously discussed BOADMs are designed to transmit both dropped and added optical carriers in the same direction of the connected fiber-ring. So a backup fiber-ring is required to eliminate the impact of any failure fiber link. To avoid the need of a backup fiber-ring, An Vu Tran et al. presented a BOADM to accomplish optical signal transmissions in both CW and CCW directions of a ring-based WDM-PON [20]. This BOADM avoids the requirement of a backup fiber-ring, but it is composed of two six-port OCs, two general FBGs, two ultra-wide reflection-window FBGs and an optical amplifier. The BOADM structure is still complicated and costly.

In order to simplify the construction of the BOADM, a novel SBOADM, as shown in Fig. 1, is proposed based on two identified FBGs, two 3-port OCs and three 4-port OCs. It is clear that all of the components are passive devices. When a group of optical carriers are fed from the left-hand side into the SBOADM, as presented in Fig. 1(a), the optical carriers can be routed from the OC1 to the OC2 and then, to the FBG1. If parts of the injected optical carriers are expected to be dropped, they will be reflected by the FBG1 and then, dropped down by the OC2 and OC3, as presented by the blue auxiliary line. The other optical carriers will then go through the SBOADM by passing through the FBG1 and OC4, as presented by the red auxiliary line. In parallel, the upstream optical carriers can be directed to the SBOADM-connected trunk-fiber by passing through the OC3 and OC1; reflected back by the FBG2 and then, leave the SBOADM via the OC1, as presented by the green auxiliary line. Similarly, if the optical carriers are fed in from the right-hand side of the proposed SBOADM, as shown in Fig. 1(b), the optical carriers can be routed from the OC4 to the OC5 and then, to FBG2. The objective optical carriers will be reflected by the FBG2 and then, dropped down by the OC5, as presented by the blue auxiliary line. The other optical carriers will then go through the SBOADM by passing through the FBG2 and OC1, as presented by the red auxiliary line. In parallel, the upstream optical carriers can be directed to the SBOADM-connected trunk-fiber by passing
The proposed optical fiber sensor network with self-healing functionality. 

Fig. 2. The proposed optical fiber sensor network with self-healing functionality.

through the OC₅ and OC₄; being reflected back by the FBG₁ and then, leaving the SBOADM from the OC₄, as presented by the green auxiliary line.

To evaluate the function of the proposal, 5 optical carriers (each with −10 dBm) are experimentally fed into the SBOADM, and only the third optical carrier is designed to be dropped. When the optical carriers are fed from the left or right-hand sides, the obtained spectra of the passed (red color) and dropped (blue color) optical carriers are presented in Fig. 1(a) inserts (ii), (iii) and Fig. 1(b) inserts (i), (iii), respectively. In parallel, when the upstream optical signal (with −10 dBm) is uploaded into the SBOADM, the optical spectrum obtained at the I/O_P1 or I/O_P2 is as presented in Figs. 1(a) inserts (i) and Fig. 1(b) inserts (ii), respectively. In this practical experiment, the insertion loss of each OC is roughly 0.8 to 1.2 dB, and the reflectance of the FBGs is 99%. In this case, the interested optical carriers will be attenuated by 0.04 dB or 20 dB when it is reflected or passing the FBG, respectively. On the other hand, for the other signals, the attenuation of passing the FBG is lower than 0.02 dB which is small enough to be ignored. So, when we observe the spectra of the passed signal, the signal which is expected to be dropped still remains in the spectra diagram but its power intensity is attenuated by about 23 dB. On the other hand, when we observe the spectra of the dropped signal, the signal is attenuated 4.5 dB which is caused by passing through the OC 4 times and being reflected by FBG once. Due to the unequal insertion loss of the OC, the reasonable attenuation value is roughly 3.2–4.8 dB ((0.8 × 4 + 0.04) ~ (1.2 × 4 + 0.04)). It can be found from Fig. 1 that the proposed SBOADM is designed to transmit the added optical carriers along the opposite transmission directions of the dropped optical carrier. When we utilize the SBOADMs to develop a ring-based all-passive optical fiber sensor network, the transmission characteristic of the SBOADM can accomplish the potential ability of avoiding fiber link failure in any one part of the ring-topology optical network.

3. Simulation Setup

Fig. 2 shows the schematic diagram of the proposed optical fiber sensor network based on the self-developed SBOADM. In the network, the FBG sensors located in the same area are seriously
connected as a sub-ring topology, and each sub-ring topology is bridged to a main-fiber ring via the proposed SBOADM. Generally, the CO may far from the FBG sensing regions. To reduce the cost of deploying optical fiber between the CO and the FBG sensing regions, we let the CO connect with the main-fiber ring by a trunk SMF (SMF₁) and an RN which is composed of a 2 * 2 SW and a 1 * 2 optical splitter (50:50) as indicated in insert (i) of Fig. 2. Ideally, the FBG sensors can be located in different regions, and the number of FBG sensors in each region can be deployed randomly and asymmetrically. The CO is designed to launch multiple optical sensing signals simultaneously or sequentially into each region of the sensor network and to receive and analyze the reflected optical signals. However, to simplify the simulation environment, the fiber laser subsystem is replaced by 12 laser diodes (LDs) (λ₁ to λ₁2 are set at 1550–1554.4 nm with a 0.4 nm channel spacing and 0 dBm power intensity). The number of sensing regions is set to 3, and the number of FBG sensors in each region is set to 4. The distance between regions is set to 1 km, and the distance between the CO and the main fiber-ring is set to 25 km. In this case, the SBOADM₁ is utilized to bridge FBG₁–₁–FBG₁–₄ located around a river (Region A); the SBOADM₂ is employed to bridge FBG₂–₁–FBG₂–₄ located in a building (Region B) and the SBOADM₃ is applied to bridge FBG₃–₁–FBG₃–₄ located around a mountain (Region C). To simulate the scenario, the reflection window of the FBGs in the SBOADM₁, SBOADM₂ and SBOADM₃ are set to 1549.84–1551.36 nm, 1551.44–1552.96 nm and 1553.04–1554.56 nm, respectively. In parallel, the reflection windows of the FBG sensors in each sensing region are set to 40 GHz and the central wavelength of those FBG reflection windows are set sequentially from the λ₁ to the λ₁₂, respectively. The FBGs in each region are in a series connection, and each end of the connection is linked to the I/O_P₁ or I/O_P₂ of the bridged SBOADM,respectively.

Under normal circumstances, the downstream optical carriers in the CO will be multiplexed by an AWG and then be transmitted to each sensing region via the SMF₁, RN, and the SBOADMs. The SW inside the RN is set in parallel status in this stage, so the downstream optical carriers will be sequentially directed to SBOADM₁–SBOADM₃. During the propagation in the main-ring topology, these optical signals will be dropped in groups to each sub-ring by the connected SBOADM and be reflected back by each indicated FBG sensor inside each region. For example, optical carriers 1–4 (λ₁ to λ₄) are dropped simultaneously by FBG₁ or FBG₂ inside the SBOADM₁ and are directed to FBG₁–₁, FBG₁–₂, FBG₁–₃ and FBG₁–₄ sequentially. If these FBGs function properly, the optical carriers 1–4 will be reflected back by these FBG sensors and be added into the main fiber-ring via the same SBOADM. These added optical carriers will then be sent back to the CO via the reverse pathway of the downstream optical sensing signals. Similarly, optical carriers 5–8 (λ₅ to λ₈) and 9–₁₂ (λ₉ to λ₁₂) are dropped to regions B and C, sequentially by SBOADM₂ and SBOADM₃ respectively.

4. Simulation Results and Discussion

It is clear from Fig. 2 that the composed optical fiber sensor network is a hybrid tree and ring topology. Under this structure, the CO can be deployed inside a city, and utilizing a trunk fiber to access the FBG sensors positioned in rural areas. Normally, the SW in the RN is in a parallel status, so the downstream optical sensing signals would be transmitted to the RN via an OC and the 25 km trunk fiber (SMF₁) and consequently, be directed to the SBOADM₁. To evaluate the proposal, we use VPI transmission maker to simulate its efficacy. The simulate optical spectra observed before SBOADM₁–SBOADM₃ (points (a)-(d) of Fig. 2) are presented in Figs. 3(a)–(d), respectively. In the previous experimental setup, the reflectance ratio of the employed FBGs was 99%, but to simulate a harsh environment, this value is set to 95% rather than 99%, so the attenuation values of the reflected and passed signals are about 0.2 dB and 13 dB rather than 0.04 dB and 20 dB. The detailed insertion loss or attenuation values of each component are recorded in Table 1. In this case, the transmission loss between the CO and the SBOADM₁ is 6.5 dB (passing through OC, 25 km SMF₁, SW at RN, 1 km SMF₂). When the optical sensing signals feed into the SBOADM₁, the λ₁ to λ₄ will be dropped down to Region A and the other optical sensing signals will pass through. Comparing
Fig. 3. (a) to (d) are the optical spectra diagrams obtained from Fig. 2’s sensing points (a) to (d), (e) and (f) are the optical spectra that detected at each region and CO, respectively.

### TABLE 1
The Detailed Insertion Loss of Each Component

<table>
<thead>
<tr>
<th>Component</th>
<th>Optical Circulator</th>
<th>Optical Switch</th>
<th>Optical Splitter</th>
<th>FBG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss(dB)</td>
<td>0.8</td>
<td>0.5</td>
<td>3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The optical spectra obtained before the SBOADM and after SMF, as shown in Figs. 3(a) and (b), the powers of $\lambda$1 to $\lambda$4 (located between 1550 nm to 1551.2 nm) are attenuated 13 dB simultaneously, and the others are attenuated roughly only 3 dB. Except for the FBG reflection ratio, the simulation results match the experimental results, as shown in Fig. 1(a) insert (ii). Similarly, $\lambda$5 to $\lambda$8 and $\lambda$9 to $\lambda$12 are sequentially dropped to regions B and C by the SBOADM and SBOADM, respectively. The optical spectra observed before and after the SBOADM are shown in Figs. 3(c) and (d), respectively. The attenuations of the dropped and passed optical carriers are 13 dB and 3 dB as well. The dropped optical carriers in each region are then sequentially routed to each FBG sensor in CW direction. After all the SBAODMs drop the optical carriers successfully, $\lambda$1–$\lambda$12 still remain at a $\sim$28.6 dBm power intensity in the network, as shown in Fig. 3(d). In this case, the rest of these optical signals will continuously be transmitted along the downstream pathway to arrive at Port 4 of the RN. Their energy will be consumed totally inside the RN because they will keep passing through a 2 * 1 optical splitter and a 2 * 2 SW in the RN. Thus, the rest of the optical signals will not influence the operation of the network.

To evaluate the downstream signals, the spectra of the dropped optical carriers in each region are detected and are shown in Fig. 3(e). Compared with the values shown in Fig. 3(a), the dropped signals in Region A are attenuated about 3.5 dB which is caused by passing OC 4 times and being reflected by FBG once (ideal value is $0.8 \times 4 + 0.2 = 3.4$ dB). Similarly, compared with the values shown in Figs. 3(b) and (c), the dropped signals in both Region B and Region C are attenuated about 3.4 dB, respectively. It is obvious that the simulation results match the experimental results (3.2 to 4.8 dB).
Inside each region, if the characteristics of the FBG sensors are not seriously changed by the located environment, the dropped optical carriers in each sub-ring will be reflected back to the connected SBOADM and then, be directed back to the CO along the reverse direction of the downstream pathway. The optical spectra of the observed reflected signals in the CO are presented in Fig. 3(f). The power attenuations of the reflected sensing signals are roughly two times of that shown in Fig. 3(e). These figures indicate that the proposed SBOADM can properly drop/add the desired group of optical carriers into/out of the sensing regions and let the other optical carriers pass through it.

If a fiber failure happens, for example, the SMF located between the SBOADM and SBOADM is broken, as shown in Fig. 4, the CO will lose the ability to detect regions B and C. In this case, we can simply restore the blocked connections by adjusting the status of the SW in the RN from parallel status to cross status. As shown in Fig. 4 insert (i), when the SW is in a cross status, the downstream optical carriers will be directed to Port 4 of the SW and the pre-installed optical splitter will route those optical carriers into two pathways. For the first pathway, those optical carriers are fed back to Port 2 of the SW and then, fed into the main-ring in the CW direction. Those optical carriers can then be routed to Region A via the SBOADM. In parallel with Pathway 1, the optical carriers in the second pathway will be directed to the main-ring in the CCW direction and then, sequentially be directed to regions C and B via SBOADM and SBOADM, respectively. Due to the bidirectional characteristic of the proposed SBOADM, whenever the downstream optical carriers are routed in a CW or CCW direction, each SBOADM in the main-ring can utilize FBG or FBG inside the SBOADM to drop a dedicated group of optical carriers into the connected sensing region and let the other optical carriers pass through. The reflected sensing signals would then be directed back to the CO via the reverse pathway of the downstream transmissions so that the breakpoint will be bypassed automatically. The optical spectra measured at the down-stream’s observed points (a)–(d) of Fig. 4 are shown in Figs. 5(a)–(d), respectively. As shown in Figs. 5(a) and (d), when the optical carriers pass through the RN, all the signals are separated and directed to the SBOADM and SBOADM. The average power value of the observed optical sensing signals in the CW and CCW directions are $-9.8$ dBm and $-9.3$ dBm, respectively. Ideally, the power attenuation between
Fig. 5. (a) to (e) show the optical spectra diagrams obtained from Fig. 4’s sensing points (a) to (e), (e) and (f) are the optical spectra that detected at each region and CO, respectively.

the CO and the RN is roughly 5.8 dB (0.8 dB + 25 km * 0.2 dB/km), and the insertion losses of the RN are 4 dB (2 * 0.5 dB + 3 dB) and 3.5 dB (0.5 dB + 3 dB) in CW and CCW directions, respectively. When these optical carriers arrive the observed points (a) and (d) of Fig. 4, the SMF₂ and SMF₅ will introduce additional 0.2 dB attenuation. The obtained optical spectra roughly match the ideal values except for a 0.2 dB power difference which may be caused by the nonlinear effect of the SMF₁.

In the CW transmission direction, the optical carriers will be blocked by the SMF₃ because of the fiber failure after passing through the SBOADM₁ so, only Region A can be successfully detected. On the other hand, the optical carriers in the CCW transmission direction would be transmitted through SBOADM₃ and SBOADM₂ sequentially, and then, be blocked by the SMF₃. Comparing the optical spectra shown in Figs. 5(c) and (d), the powers of optical signals located between 1553.2 nm to 1554.4 nm are simultaneously attenuated 16 dB but all of the other optical carriers are only attenuated roughly 3 dB. This indicates that those optical signals are dropped to Region C simultaneously by the SBOADM₃ and the other optical can go through the SBOADM₃ properly. Similarly, if we observe the optical spectra shown in the Figs. 5(b) and (c), the SBOADM₂ can also drop the dedicated group of optical carriers (1551.6 nm to 1552.8 nm) to sensing Region B, respectively, and each optical carrier in the sensing region is sequentially routed to each FBG sensor in the CCW direction. The spectra of the dropped optical carriers in each region are shown in Fig. 5(e), and the optical spectra of the reflected optical carriers observed at the CO are presented in Fig. 5(f). For the dropped optical carriers, the power variation for each adjacent group is roughly 3 dB which is caused by the attenuation of additional SMF and SBOADMs. In correlation with the power of the dropped signals, the power of the reflected sensing signals observed in the CO are −25.6 dBm, −30.6 dBm and −25.6 dBm for regions A, B and C, respectively. The power attenuations are roughly two times of that shown in Fig. 5(e). These results prove the advancement of the proposal to easily overcome any one fiber link failure based on the self-developed SBOADM.

5. Conclusion
The application of FBG sensing techniques has arisen significantly recently. To maintain the resilience of optical fiber sensor networks, two types of self-healing schemes have been proposed to
avoid the impact of a fiber link failure. Nevertheless, the requirements of providing a power supply, a complicated control methods and notable insertion loss of employed devices make both methods unsuitable for large scale optical fiber sensor networks. To combine the advancement of both methods, a novel passive SBOADM is proposed and is employed to set up an optical fiber sensor network in a hybrid tree and ring topology. Experimental results prove that the SBOADM can drop the desired optical signal in both cases that the optical signals insert from left hand side or right hand side, and the added optical carriers can be transmitted back along the opposite transmission directions of the dropped optical carrier. The maximum insertion losses of the dropped and added optical signal are 4.5 dB and 3.4 dB, respectively. By reasonably utilizing the bidirectional routing characteristics of the SBOADM to bridge each FBG sensing region with the main fiber-ring of the network and employing a $2 \times 2$ optical switch and a $1 \times 2$ optical splitter as an RN to bridge the CO with the main fiber-ring, the optical sensing signals generated from the CO can be transmitted through the trunk fiber to the RN and be communicated inside the main fiber-ring in a CW direction or in both the CW and CCW directions according to the status of the optical switch in the RN. Simulation results show that when any one part of the main fiber-ring or the FBG sensing regions is blocked, the connection can be recovered easily by adjusting the status of the $2 \times 2$ optical switch inside the RN to direct the optical sensing signals in both CW and CCW directions. The induced power penalty to recover the blocked connection is roughly 6 dB. These results prove that the proposed architecture has great expandability and can achieve self-healing functionality without utilizing a complex control scheme and electrical power supply in each sub-fiber sensor network.

References


