LETTER
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Autonomous self-healing technique utilizing a self-injection-locked Fabry-Perot laser for optical and wireless communication systems

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Abstract: An autonomous self-healing technique utilizing a self-injection-locked Fabry-Perot laser is proposed for optical and wireless seamless communication systems. The proposed technique is more promising than the other techniques because of its high reliability and simple configuration. It has been experimentally confirmed that the self-healing technique can be adopted in optical and wireless communication systems with plural wireless back-up links.

Keywords: Fabry-Perot laser, injection-locking, self-healing, optical fiber failure, optical and wireless seamless communication system
Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

As optical fiber transmission systems convey large capacity data for providing broadband applications and services, optical fiber failures caused by disasters have a significant impact on social networks [1]. While a technique for recovering failed links by redundant fibers has been reported [2], there is a possibility that the redundant links are simultaneously damaged in the case of large-scale disasters. Optical fiber failures are likely to occur at specific sections such as paths along bridges, embankments and cliffs, and therefore, wireless back-up links preliminarily installed at the specific sections can rapidly recover failed links. Radio-over-Fiber (RoF) is one of the promising technologies because it has a capability of optical and wireless seamless transmission [3, 4]. From this perspective, we study a RoF-based optical and wireless communication system with rapid recovery capability against disasters. In this system, a self-healing functionality is required for detecting optical fiber failures and autonomously switching to the back-up links. In addition, optical and wireless switching nodes which are pre-installed at hazardous sections are needed to be as simple as possible for ensuring high reliability. While a self-healing technique based on mutual-injection-locked Fabry-Perot lasers (FP-LDs) was previously reported in Ref. [5], the technique is not sufficiently reliable for disasters because it may falsely operate in the case of some equipment failures.

In this paper, we propose an autonomous self-healing technique utilizing a self-injection-locked FP-LD. The proof-of-concept experiments verify that the proposed technique is feasible because of its high reliability and simple configuration.

2 Optical and wireless seamless communication system

A conceptual diagram of the optical and wireless seamless communication systems is shown in Fig. 1, where wireless back-up links are pre-installed at plural sections in an optical fiber transmission line between the central offices (COs) -1 and -2. The optical transmission bit-rate and the total distance between the COs-1 and -2 are assumed to be 100 Gbit/s or more and several tens of kilometers, respectively. When optical fiber failures occur, the bit-rate should be decreased due to the restriction of RoF transmission capacity in wireless sections, and thus, it is assumed that the bit-rate in the case of fiber failures is decreased to 10 Gbit/s or more. The distance of wireless back-up links is assumed to be 1 km or less, corresponding to the distance of optical fiber links between the nodes-1 and -2. When optical fiber failures are caused by a disaster at the sections-1 and -2 as shown in Fig. 1, the failed links are switched to wireless back-up links. It is preferable that the switching can be completed as soon as possible, within the order of seconds, in order to recover lifeline utilities provided on the network such as safety confirmation systems, emergency calls, and so on. For switching to wireless back-up links reliably and rapidly, the following operations are required:

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(i) All the switching process including the failure detection should be completed only in physical layer to reduce the complexity of the configuration and the latency caused by signaling.
(ii) The switching should be autonomously operated to save the time that network operators go to the failed sections.
(iii) The switching should be independently operated in each section to avoid the isolation from the COs. For example, in the case that link failures occur in sections-1 and -2 as shown in Fig. 1, the section between the node-2 in section-1 and the node-1 in section-2 is isolated and these nodes cannot communicate with the COs.

As for the failure detection technique in physical layer described in the requirement (i), an optical time domain reflectometer (OTDR) is a promising candidate [6]. However, it cannot satisfy the requirements (ii) and (iii) because it detects only the first failure point closest to the COs. There is another type of detection technique monitoring the change of states-of-polarization (SOP) [7], but the configuration is too complicated to fulfill the requirement (i). It needs monitoring the temporal variation of SOP precisely. From these reasons, we propose a new technique that can meet all the requirements (i) to (iii) in the next chapter.

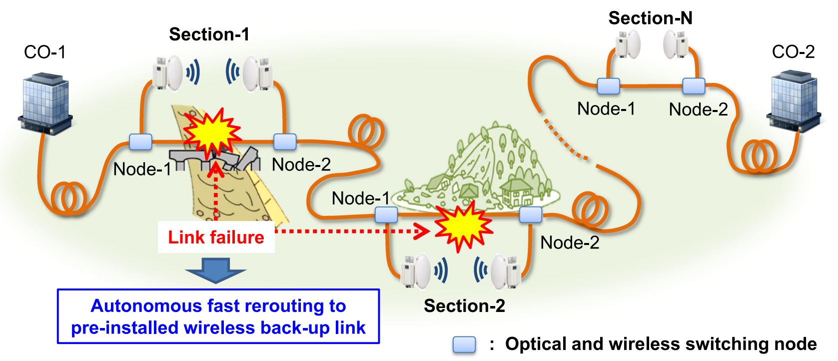

Fig. 1. Schematic illustration of the optical and wireless seamless communication systems.

3 Autonomous self-healing technique

The proposed autonomous self-healing technique is based on the detection of the state change of an injection-locked FP-LD [8]. The self-healing operation is simple because it does not require complicated signal processing, and thus, the high reliability of self-healing operation can be ensured.

Fig. 2 shows a schematic diagram of the proposed autonomous self-healing technique utilizing a self-injection-locked FP-LD, where only the uni-directional operation from the node-1 to -2 is depicted for simplifying the explanation. When the optical fiber between nodes-1 and -2 is cut off, the failed link is switched to a wireless back-up link. An optical and wireless switching node consists of a FP-LD for monitoring the state of the fiber link, an optical coupler (CPL) for dividing the light emitted from the FP-LD, a wavelength

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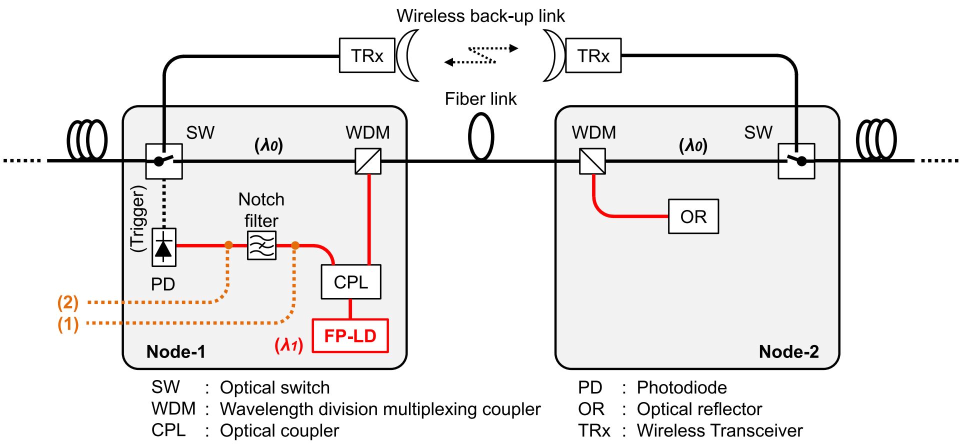

Fig. 2. Schematic diagram of autonomous self-healing technique utilizing a self-injection-locked FP-LD for optical and wireless seamless communication systems.

division multiplexing (WDM) coupler for combining an optical data signal and the light emitted from the FP-LD, an optical reflector (OR) for inducing the self-injection-locking state of the FP-LD, an optical notch filter and a photodiode (PD) for monitoring the locking state of the FP-LD, and an optical switch (SW) for switching the path according to the monitored result. The FP-LD in the node-1 emits light around the wavelength of λ_1, which are different from the optical data signal wavelength of λ_0, at the free-running state. The light at λ_1 is then spectrum-sliced by the WDM coupler, and is reflected by the OR in the node-2. The reflected light is returned to the FP-LD in the node-1, and thus, the self-injection-locking state of the FP-LD is created. The optical spectra of the injection-locked or unlocked FP-LD monitored at the points (1) and (2) designated in Fig. 2 are shown in Figs. 3(a) to (d), respectively. In the injection-locking state, the FP-LD emits light with a narrow spectrum at 1550 nm (Fig. 3(a)), and the optical power passing through the notch filter is too low to be detected by the PD (Fig. 3(b)). On the other hand, when an optical fiber failure occurs, the FP-LD is turned to the unlocking state (Fig. 3(c)), and the light passing through the notch filter is injected into the PD (Fig. 3(d)). A trigger signal, which is generated by a simple analog circuit for the adjustment of the output from the PD, drives the SW to change the connection path from the fiber link to the wireless back-up link. Hence, the self-healing operation can be autonomously completed. The proposed technique has high reliability for failure detection because it detects the light emitted from the FP-LD only in the case that optical fiber failures occur. The self-healing operation employing the proposed technique can be completed only in physical layer. In higher layer, a function of monitoring the switching node status in control plane is necessary in the COs for changing the bit-rate. Thus, the total time to complete the switching of the whole system would be long, compared to the switching time in physical layer.

Figs. 4(a) and (b) show the alternative self-healing techniques based on the distributed feedback lasers (DFB-LDs) and on the mutual-injection-locked FP-LDs, respectively. In the configuration (a), the DFB-LDs-1 and -2

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in the nodes-1 and -2 emits light toward the nodes-2 and -1, respectively, and the optical fiber failure can be detected by monitoring optical received power at the PDs-2 and -1. In the configuration (b), the FP-LDs-1 and -2 in the nodes-1 and -2 are mutually injection-locked with each other, and the optical fiber failure can be detected by changing to the locking state of FP-LDs [5].

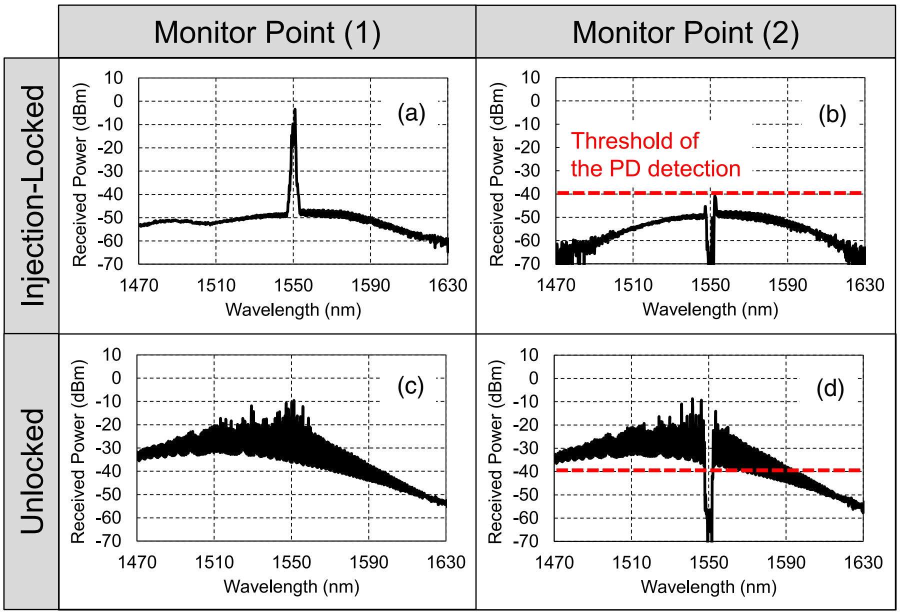

Fig. 3. Optical spectra monitored at the points (1) and (2) in Fig. 2.

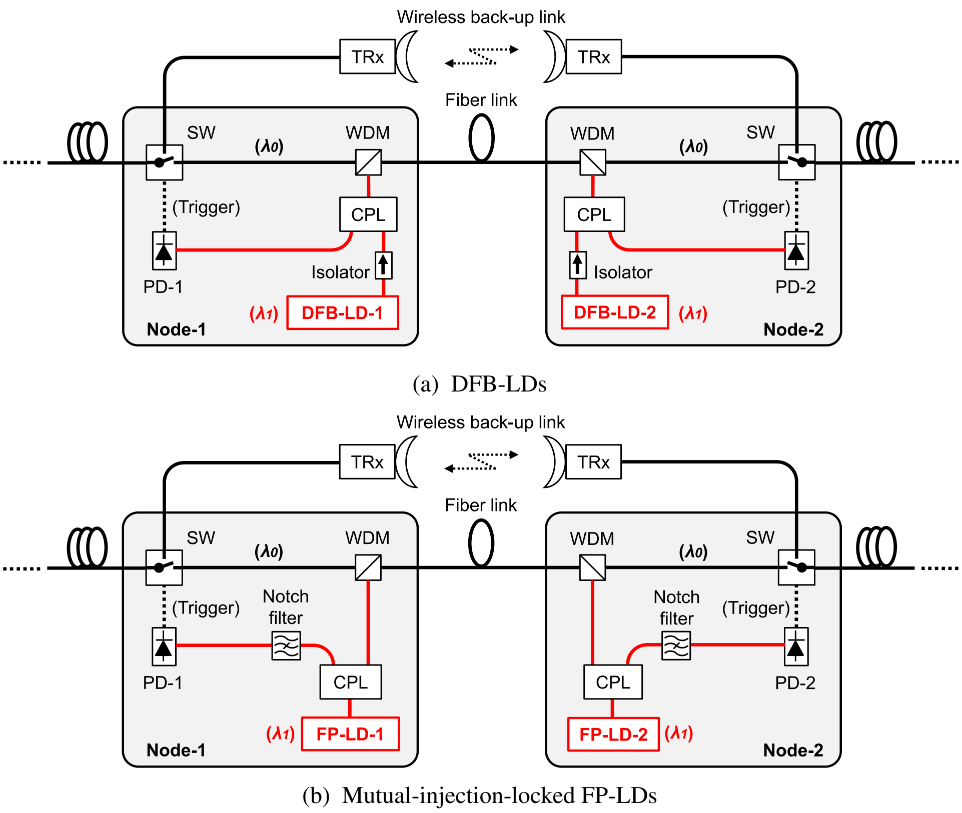

Fig. 4. Alternative configurations of self-healing techniques.

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The result of comparison among three techniques in terms of the reliability for self-healing operation is summarized in Table I. It is desired for the autonomous switching to operate only when optical fiber failures occur. In the DFB-LD-based technique, however, the switch is falsely operated in the cases of the DFB-LD and/or PD failures. As for the mutual-injection-locked FP-LDs, the false operation is caused in the case of the laser failure, and consequently, the self-healing operations based on these two techniques are not sufficiently reliable against disasters. For the mutual-injection-locking scheme, the temperature of the two FP-LDs must be adaptively controlled to keep the locking state. When the difference of the temperature between the two FP-LDs becomes large, the state is changed to be unlocked.

On the other hand, even in the cases of the optical component failures such as FP-LD and PD, the self-injection-locked FP-LD can properly operate because it uses a loop-back configuration. In addition, it does not require the temperature control of the FP-LD since it can be injection-locked by the light emitted from itself. Hence, compared to the other two techniques, the self-healing technique based on the self-injection-locked FP-LD is the most promising because of its high reliability and simple configuration.

Table I. Comparison among three self-healing techniques.

Techniques	Switching operation in the case of each failure		
	Fiber failure	LD failure	PD failure
DFB-LDs	**Switch**	**Switch**	**Switch**
Mutual-injection-locked FP-LDs	**Switch**	**Switch**	**Hold**
Self-injection-locked FP-LD	**Switch**	**Hold**	**Hold**
Desired operation	Switch	Hold	Hold

4 Experiments for autonomous self-healing operation

The proof-of-concept experiments of autonomous self-healing operations employing the detection technique utilizing a self-injection-locked FP-LD were conducted with a setup shown in Fig. 5. A FP-LD at the central wavelength of 1550 nm was located in the node-1 for monitoring the state of 1 km-long single-mode fiber (SMF). The DFB-LD emitted light at the wavelength of 1535 nm as a light source emulating an optical data signal. The light emitted from the FP-LD looped back to the node-1 after being reflected by the OR in the node-2, and the FP-LD was self-injection-locked. The pass-bands of the wavelength division multiplexing (WDM) couplers were 1550 ± 1.5 nm, and the rejection bandwidth of the optical notch filter was 3 nm. The PDs-1, -2, -3 and -4 monitored the optical powers of the injection light into the FP-LD, that after the optical notch filter, that output from the 1×2 SW to the SMF and that output from the 1×2 SW to the wireless back-up link, respectively. The failure of the SMF was emulated by switching a 1×1 SW placed between the nodes-1 and -2, and the evolution of optical powers monitored by the PDs-1 to -4 were measured.

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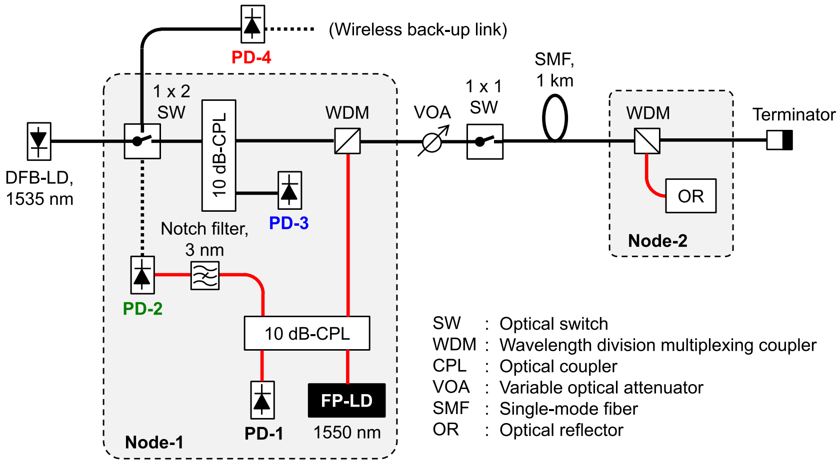

Fig. 5. Setup for autonomous self-healing experiments.

The optical power received by the PD-2 as a function of the optical injection power into the FP-LD is shown in Fig. 6. The horizontal and vertical axes are "the injection power into the FP-LD" and "the optical power measured by the PD-2 designated in Fig. 5," respectively. The injection power into the FP-LD was changed by adjusting the variable optical attenuator (VOA) inserted between the node-1 and 1 × 1 SW in the experiment. It is shown that the state of the FP-LD gradually varies from the injection-locking state to the unlocking state when the injection power becomes less than about −10 dBm. As the optical output power from the FP-LD used in the experiment was +8 dBm, the round-trip optical transmission loss can be allowed up to 18 dB for keeping the injection-locking state, and thus, the power budget between the nodes-1 and -2 corresponds to a half of 18 dB. The polarization dependence of the reflected light for the injection-locking was measured to be 0.9 dB, which is a relatively small value although the FP-LD is not specially designed nor optimized. Therefore, the self-healing technique can be applied to the systems with optical power budget of 8 dB after subtracting 1-dB polarization dependence.

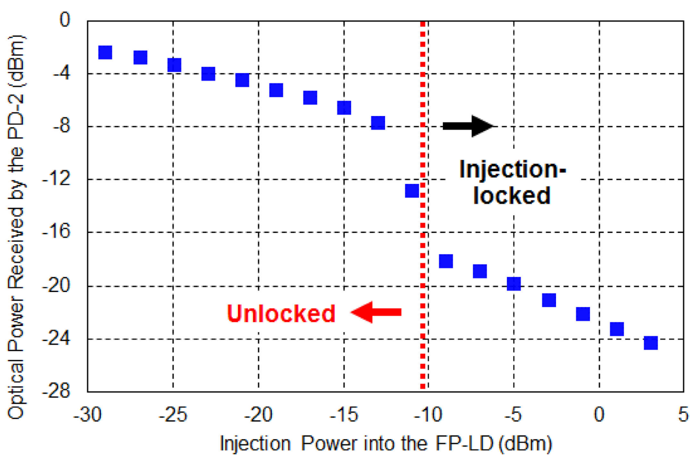

Fig. 6. Optical power received by the PD-2 as a function of the injection power into the FP-LD in Fig. 5.

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Fig. 7 shows the optical powers received by the PDs-1 to -4 as a function of elapsed time. These results indicate that the FP-LD turned to the unlocking state by the optical fiber failure, subsequently the received power at the PD-2 increased, and finally, the 1×2 SW was correctly switched from the failed optical fiber link to the wireless back-up link. The optical failure detection time was as small as 0.13 ms, and the total self-healing time including the stabilization of the 1×2 SW was 2.4 ms. The switching speed would be sufficiently rapid to be adopted in optical and wireless seamless communication systems. Thus, it was confirmed that the proposed technique can rapidly recover the failed optical fiber links with high reliability and simple configuration. The application of the proposed technique is not necessarily limited to optical and wireless seamless communication systems. For example, in future passive optical networks that provide broadband services to hundreds of subscribers via an optical fiber, failure at a single point should have a significant impact. In such a case, the fiber failure can be promptly recovered by deploying the self-healing nodes at critical points along the optical fiber line, while the redundant links are not necessarily limited to wireless links.

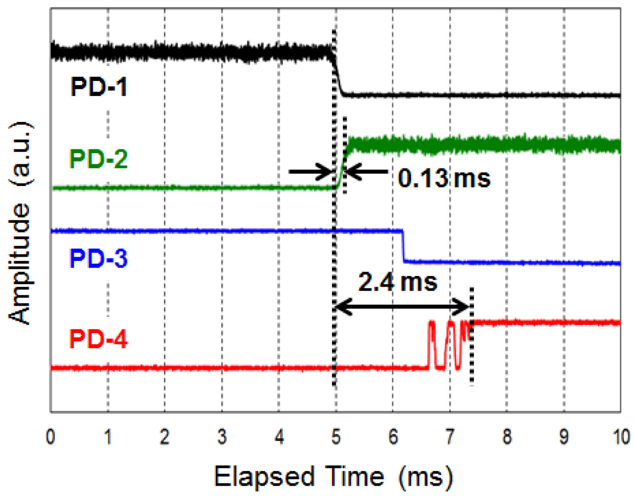

Fig. 7. Optical powers received by the PD-1 to PD-4 in Fig. 5 as a function of elapsed time.

5 Conclusion

An autonomous self-healing technique utilizing a self-injection-locked FP-LD was proposed for optical and wireless seamless communication systems. Compared to the other techniques with a similar configuration, the proposed technique is the most promising for the self-healing operation because of its high-reliability and simple configuration. The failure detection time of 0.13 ms and the total self-healing operation of 2.4 ms were experimentally confirmed, which are rapid enough to be adopted in the practical systems. The self-healing technique is practically effective for satisfying the social demands on the optical fiber transmission systems that can be rapidly recovered from disasters.

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