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Fault detection technique for wavelength division multiplexing passive optical network using chaotic fiber laser

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ABSTRACT

We propose a fault localization method for wavelength division multiplexing passive optical network (WDM-PON). A proof-of-concept experiment was demonstrated by utilizing the wavelength tunable chaotic laser generated from an erbium-doped fiber ring laser with a manual tunable fiber Bragg grating (TFBG) filter. The range of the chaotic lasing wavelength can cover the C-band. Basing on the TFBG filter, we can adjust the wavelength of the chaotic laser to match the WDM-PON channel with identical wavelength. We determined the fault location by calculating the cross-correlation between the reference and return signals. Analysis of the characteristics of the wavelength tunable chaotic laser showed that the breakpoint, the loose connector, and the mismatch connector could be precisely located. A dynamic range of approximately 23.8 dB and a spatial resolution of 4 cm, which was independent of the measuring range, were obtained.

1. Introduction

Wavelength division multiplexing passive optical networks (WDM-PONs) are emerging as next generation access networks because they offer several advantages, such as large capacity, network security, easy management, and upgradability. A WDM-PON system can carry high-capacity data to numerous users, suggesting that fault monitoring is essential to ensuring system reliability. Thus, optical time domain reflectometry (OTDR) is crucial in the communication systems to reduce the downtime caused by a fault in WDM-PON. However, conventional OTDR only operates at a single wavelength and is thus not suitable for WDM-PON because of the arrayed waveguide grating (AWG) placed at the remote node. This unsuitability is caused by the blocking of the OTDR pulse at remote node. If a fault occurs in the drop fiber, the location cannot be identified. Tunable OTDR has been proposed by using wavelength tunable laser pulse to solve this problem [1–3]. However, the tradeoff between dynamic range and spatial resolution exist in pulse OTDR. The utilization of ultrashort pulse in improving spatial resolution requires complicated techniques and increases operational costs. A number of researchers have proposed wavelength tunable sequence OTDR [4,5], which utilizes a wavelength tunable or swept laser modulated by an electrical pseudo-random sequence as probe light. This method can enhance dynamic range without reducing spatial resolution. However, spatial resolution remains limited by the electronic bandwidth.

In addition, fault localization by reusing the downstream light sources has been proposed [6]. This method utilizes an OTDR pulse, instead of data, to modulate the downstream light source. However, the dynamic range and the spatial resolution remain dependent on the peak power of the OTDR pulse. A number of researchers proposed the use of broadband light sources in detecting faults in WDM-PON [7–10]. However, optical reflectors, such as mirror, fiber Bragg grating, and reflector of ONU vertical cavity surface-emitting laser (VCSEL) transmitter, are used at each optical network unit (ONU). These solutions require all ONU upgrades to include the optical reflectors and to use VCSELs as upstream transmitters. As the monitoring system of WDM-PON, it should be highly efficient and precise in detecting a fault but should reduce operational costs.

Chaotic OTDR has been recently reported [11,12] as a new method for fault detection; however, the longitudinal mode spacing of the laser is unequal to that of the AWG, indicating that the number of match modes is limited and that more channels cannot be detected. The output wavelength tunable chaotic laser of the Fabry–Perot laser is influenced by the feedback strength and the

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wavelength mismatch between the filter and laser modes; thus, the output wavelength of chaotic lasers cannot be continuously tuned [11]. Moreover, the autocorrelation detection of the chaotic signal induces side lobes [12], and the chaotic laser is optical wideband signal, so the dynamic range is limited by the low power of single wavelength after filtering [13]. However, side lobes bring noise into the measurement and affect the dynamic range. A high side lobe may become a "ghost peak," which causes fault misjudgment.

In this paper, we propose a new tunable chaotic OTDR to monitor WDM-PON. We use the wavelength tunable chaotic laser generated from an erbium-doped fiber (EDF) ring laser as a probe light; such laser can provide the identical wavelength of all branches in WDM-PON. In addition, the characteristics of the wavelength tunable chaotic laser are analyzed, and the results show that the performance of the proposed tunable chaotic OTDR has been successfully evaluated.

2. Characteristics of wavelength tunable chaotic OTDR

Fig. 1 shows the experimental setup of the proposed tunable chaotic OTDR for monitoring WDM-PON. The wavelength tunable chaotic laser is shown in the dashed box. The length of cavity is about 10 km. The cavity of the chaotic fiber laser comprises a 980 nm laser diode (LD) with the maximum pump power of 250 mW used to pump EDF through a 980/1550 nm wavelength division multiplexer (WDM). A manual tunable fiber Bragg grating filter (OETFG-100, Tunable range: 30 nm, Resolution: 0.1 nm) with −3 dB bandwidth of 0.6 nm is used to satisfy that of the AWG. To confirm that no significant power loss occurs at the AWG because of spectral mismatch, the −3 dB pass bandwidth of AWG is approximately 0.7 nm and the channel spacing of AWG is 100 GHz in our experiments. A polarization controller (PC) changes the polarization states of the light, and an optical isolator ensures the unidirectional transmission of the light in the cavity. The output of the chaotic laser is obtained from the 10% output of the optical coupler (OC1). The chaotic laser is then split into two beams by a 95:5 optical coupler (OC2). The chaotic laser from the 95% port acts as the probe signal, whereas the other acts as the reference signal. For detection, the probe signal is launched into a WDM-PON under test and received by an optical circulator (OC3). The reference signal and the return signal were converted into electrical signals by two identical photoelectric detectors (1 GHz bandwidth). Finally, a real-time oscilloscope (LeCory SDA806Zi-A, 6 GHz bandwidth) records the reference and return signals. We record signals with length of 0.2 ms (2 M points with sampling rate of 10 Gsa/s). A computer is used to process the data in accordance with cross correlation method.

In our experiments, we set the bias current of the 980 nm LD to 400 mA. By adjusting the PC to a proper state and tuning the TFBG filter with the tunable range of 30 nm from 1530 nm to 1560 nm, the wavelength of the chaotic laser can be adjusted to match the channel of the AWG with identical wavelength. An optical spectrum analyzer (Agilent86140B), a radio frequency (RF) spectrum analyzer (AgilentN9020A), and a real time oscilloscope are used to observe the chaotic laser. We use a PD with 12 GHz bandwidth to effectively observe the characteristics of the chaotic laser. The amplified spontaneous emission (ASE) from an EDF has a broad spectral range that covers the entire C-band, as shown in Fig. 2(a). Thus, the wavelength of the chaotic laser can be tuned to match the channel of the WDM-PON with identical wavelength because of this broad spectral range. In our experiments, the number of the chaotic wavelength is limited by the tunable range of the TFBG filter (Fig. 2(b)).

In addition, the characteristics of chaotic laser, including time series, RF spectra, and autocorrelation curves, are analyzed at wavelength of 1554.04 nm (Fig. 3.) The time series of the chaotic laser presented noise-like characteristics (Fig. 3(b)). Chaotic signals have a wideband spectrum, which can reach 12 GHz (Fig. 3(c)). The inset in Fig. 3(c) shows the details of the chaotic signal with a span of 300 MHz. Because of the ring cavity in our experiment has its own unique feature, it can be seen from Fig. 3(c) that the spectrum is flat and no information about the cavity. The autocorrelation curves of the chaotic laser signal have a delta-function-like characteristic, which is not related to the change in wavelength (Fig. 3(d)). The comparison shows that the outputs at other wavelengths have similar time and frequency domain characteristics. Therefore, chaotic laser signal can be used as an ideal ranging signal.

3. Experiment results

Considering the delta-function-like characteristic of the autocorrelation curve of the chaotic laser, we calculate the cross-correlation between the reference and return signals to locate the fault position. The function of the reference signal is expressed by $x(t)$; the return signal is denoted by $k \cdot x(t-\tau)$; k is the loss coefficient; and τ is the delay time with respect to the reference signal transmission in the fiber. The cross-correlation function of the two signals can be expressed as follows:

$$x(t) \otimes k \cdot x(t-\tau) \approx k \cdot \delta(\tau)$$

where $\otimes$ represent the convolution operation. We can locate the fault position by calculating $c \cdot \tau / 2n$, where c is the light velocity in a vacuum and n is the refractive index of fiber. We obtain the location of fault according to the position of correlation peak.

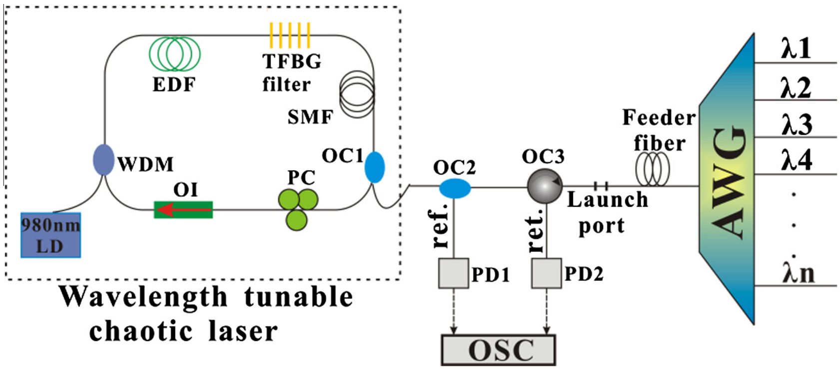

Fig. 1. Experimental setup of the proposed technique for the localization of the failures in WDM-PON.