Development of Optical Fiber Monitoring in Communication Systems

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Abstract: **Recent progress on optical fiber monitoring in the optical communication systems is reviewed along with current optical fiber monitoring and diagnosing problems in deployed access, trunk and submarine communication systems.**

Keywords: Optical fiber monitoring, diagnosis, PON monitoring, OFDR, OTDR

I INTRODUCTION

Optical fiber networks began to be deployed for submarine and trunk systems in the 1980s in Japan to meet the demand for broadband communication. Fiber-to-the-home (FTTH) services were first introduced in 2001, and their provision to subscribers has spread rapidly over the access networks. The number of FTTH subscribers in Japan exceeded 23 million at the end of 2012 [1]. The number of subscribers is increasing, and a large number of optical fiber cables are being installed daily to meet this demand. Design, construction and maintenance technologies are of fundamental importance if we are to ensure the reliability of optical communication systems. For the efficient maintenance and operation of optical fiber networks, attention has been focused on optical fiber monitoring. The basic functions of optical fiber monitoring in communication systems are designed to investigate for faults in optical fiber lines and tolocate the fault with the appropriate resolution as a post-fault maintenance activity. The optical reflectometry is a promising technology for use in optical fiber monitoring in communication systems since operators can perform tests from central offices (or remotely via a network) without installing any equipment in the customer's house. This paper focuses on the optical reflectometryand reviews optical fiber monitoring and applications that are deployed in current optical fiber networks. This paper also presents a review of recent developments in optical fiber monitoring within our group, along with the diagnosing problems with access, trunk and submarine fiber networks.

II. OPTICAL FIBER MONITORING IN CURRENT OPTICAL FIBER CABLE NETWORKS

In this section, we review optical fiber monitoring based on the optical time domain reflectometry (OTDR) and related configurations deployed in current optical access, trunk andsubmire cable network.

2.1 Access network

An optical fiber line testing system has been deployed to support the construction, reconfiguration, and maintenance of a large number of optical fiber lines in access networks [2, 3]. It performs various types of the optical test remotely, and its functions shows the configuration of an optical fiber line system used in optical access networks. An operator in a maintenance center sends orders via a data network to the optical testing module (OTM) telling it to perform various tests. The OTM, which is installed in an optical distribution frame (ODF), contains various types of optical fiber measurement equipments such as an OTDR unit, a light source for optical fiber identification, and a power meter. An optical switch called a fiber selector selects the target fiber, and an optical coupler introduces the test light into the target fiber. During construction work, OTDR test is performed to measure the loss and reflectance at splice points with a typical resolution of around twenty meters. When responding to breakdowns or complaints, it is used to distinguish faults between the transmission equipment and an optical fiber line and to identify the fault location.

A reflector installed in front of an optical network unit (ONU) at a subscriber's house cuts and reflects the test light from the OTM while allowing the communication light from the optical line terminal (OLT) to pass. A fiber Bragg grating, which has a sharp cutoff characteristic and high reflectivity, is used for the reflector. Therefore, we can carry out in-service testing without affecting the transmission quality. The wavelength of the test light is 1650 nm, which is sensitive to the fiber bending loss, in compliance with ITU-T L.41 [4].

2.2 Trunk network

Optical trunk networks are important communication lines between central offices and have a typical span length of up to about 80 km. It differs from an optical access network in that there are fewer fibers in the cables, and it uses a pair of fibers as upstream and downstream transmission lines. In general, optical trunk lines are relatively low loss and extend over long distances compared with optical access networks. The OTDR is also used for testing after construction, fault and periodic testing with a typical resolution of several hundred meters. When the link loss of an optical trunk line exceeds the dynamic range of the OTDR, bidirectional measurement is carried out from both ends of the optical trunk line.

Since optical trunk lines, which accommodate, for example, dense wavelength division multiplexing (DWDM) and coarse WDM (CWDM) transmissions, may carry a high total optical power, several technical considerations are required as regards nonlinear effects such as spontaneous Raman scattering in relation to in-service testing [5]. In accordance with the requirements of the transmission equipment, spectral attenuation and dispersion characteristics such as chromatic dispersion and polarization mode dispersion (PMD) attributed to existing optical fiber cables are occasionally verified when the transmission systems are developed.

2.3 Submarine network

Optical submarine cable systems are divided into two categories. One category consists of repeatered systems for long-haul applications, which transmit signals over thousands of kilometers by using optical amplifiers [erbium doped fiber amplifiers (EDFAs)] and power fed through submarine cables. The other category consists of repeaterless systems for short-distance applications of up to several hundred kilometers. To monitor the long submarine optical fiber cable, a coherent OTDR (C-OTDR) is employed to improve the receiver sensitivity up to the quantum limit by heterodyne detection, which is advantageous for the direct detection. A typical resolution of over one kilometer is used for submarine applications. Roughly speaking, a repearterless system has basically the same monitoring aspect as that in optical trunk networks. In repeatered systems, the EDFA contains optical isolators and auto-level control (ALC) circuits to stabilize the gain characteristic of communication signals passing through the repeaters. Figure 3 shows a typical monitoring configuration for repeatered submarine systems [6].

Since the optical isolator rejects any backscattering light from the second and subsequent spans of the transmission line, an optical coupler with a typical coupling ratio of 1:10 connects the downstream and upstream lines. The backscattered light generated in the second and subsequent spans of the downstream line propagates back along the upstream line via the backscattered paths incorporated in each repeater and then detected in the C-OTDR. The repeater gain, fiber loss, and fiber fault location are monitoring parameters [7].

III. RECENT RESEARCH ON OPTICAL FIBER MONITORING IN COMMUNICATION SYSTEMS

3.1 End-reflection assisted Brillouin analysis for PON branch monitoring

A. Issues with current monitoring in access networks

There is one of difficulties to maintain the passive optical network (PON) widely installed in access networks, in which an optical power splitter is installed outside. The simple OTDR approach at a central office provides only a superposition of the reflectometric traces of all branches. The high resolution OTDR is one of the few practical ways in

the current situation whereby operators can confirm the number of reflections at the FBG reflector in the traces, but its use is limited to checking for the presence of fiber breaks [8]. Otherwise, operators have to undertake testing from inside the customer's house [9]. The above problem is widely recognized as a research topic of interest in optical fiber monitoring.

Many approaches have been reported including the multi-wavelength OTDR with wavelength dependent devices [10, 11] and Brillouin OTDR with devices that have different Brillouin frequency shifts [12]. However, these techniques require additional optical components or changes to the optical fiber itself. Therefore, they are difficult to apply to existing PONs. Recently, we have proposed and developed a technique to overcome this problem, namely to enable us to monitor the individual loss distribution of PON branches from the central office for the configuration shown in Fig. 2 without any change in the installed facilities [13, 14]. We call this approach end-reflection assisted Brillouin time domain analysis. The next subsection presents a review of recent achievements regarding this technique including the measurement of a 32-branched PON, with a dynamic range of about 25 dB.

B. End-reflection assisted Brillouin analysis

The test beam consists of a probe pulse accompanied by a pump pulse with a temporal interval of $\Box t$. Their optical frequencies are set such that a Brillouin interaction occurs, and the probe pulse is amplified when the two pulses collide at a distance of $\Box\Box t/2$ from the reflection point at the end of the optical fibers ($\Box$: light velocity). Since the Brillouin gain is proportional to the pump power at the collision, the optical loss at the collision point in every branch can be obtained by observing the probe pulse gain caused by the interaction. To distinguish the branches requires the difference in the lengths of the branches, namely, a length difference that exceeds the probe pulse width is needed between every pair. In other words, when a small length difference is included in the measured PON, a short probe pulse must be used. Consequently, a large bandwidth is needed, and the sensitivity is decreased. The length difference (and probe pulse width) should

be larger than the lifetime of an acoustic phonon, otherwise the gains of two branches with similar lengths cannot be distinguished. The event spatial resolution of the system is determined by the smaller of the two values, namely the pump and probe pulse widths. A larger pump pulse width yields a larger gain, thus improving the sensitivity. In a laboratory test of the described method, where a PON test-bed was constructed by using standard single-mode fibers (SSMFs) and optical couplers, we demonstrated the measurement of a 32-branched PON with a minimum branch length difference of 2 m. The loss distribution of every branch was successfully obtained. The signal-to-noise ratio (SNR), or dynamic range of the measurement system was analyzed and examined experimentally. We found that the sensitivity of the measurement was mainly determined by the receiver noise, which was combined with the probe beam when analyzing the Brillouin gain. However, in some cases, the spontaneous Brillouin scattering yielded at all the branches and combined at the receiver may exceed the receiver noise and be a limiting factor as regards the sensitivity. In a laboratory test with a minimum length difference of 2 m, an event resolution of 10 m, an input pump power of +16 dBm, and assuming a uniform Brillouin frequency shift (BFS) value throughout the fiber, we obtained a dynamic range of about 25 dB with 10000-time averaging (1~2 minutes measurement time). Further investigation is now under way to respond the BFS variation in the field, maintenance wavelength for in-service testing, intended for the practical use in optical access networks.

3.2   Long-range C-OFDR for identifying high-PMD section along installed cables

A. Issue with legacy cables in trunk networks.

The PMD of the optical fiber is an importantfactor when designing large capacity transmissionsystems. In particular, legacy fibers installed intrunk networks prior to the early 1990s often exhibithigh PMD values that are unsuitable for high-speedtransmission. Although the digital coherenttechnology significantly mitigates the stringentrequirement for decreasing PMD, in terms of fibermanagement, it is very useful to know thedistribution of such a large birefringence

along allinstalled fibers.The polarization-sensitive optical time domainreflectometry (P-OTDR) [15] is a useful tool formeasuring the states of polarization (SOP) of backscattered lightwaves, from which we can know the beat length. Techniques for calculating birefringence, or even PMD, by employing the backscattered SOP measured with the P-OTDR, have progressed greatly [16–20]. However, the spatial resolution of the P-OTDR is limited to about 1 m, and this is often insufficient to recognize the short beat length induced by a high birefringence. The coherent optical frequency domain reflectometry (C-OFDR) provides a narrow spatial resolution for detecting the birefringence of high- PMD fibers [21, 22]. However, its measurement range is limited by the coherence length of the optical source. To maintain a narrow spatial resolution while extending the measurement range, we have proposed and developed the phase-noisecompensated OFDR (PNC-OFDR) [23] and obtained a sub-cm spatial resolution over 40 km in a normal laboratory environment [24]. In this subsection, we describe the application of the PNC-OFDR to locate sections with high birefringence along installed optical cables. We found that an installed fiber occasionally included polarization beat lengths as short as a few tens of cm, which are very difficult to observe with the P-OTDR.

B. Phase noise compensated C-OFDR (PNCOFDR) and distributed birefringence measurement [23–26]

The configuration and principle of the PNC-OFDR. The setup consists of two interferometers: a measurement interferometer (MI) and a reference interferometer (RI). The probe beam is divided into two equal portions, which are simultaneously incident to the MI and RI. The MI collects backscattered beam data from the fiber under test (FUT) as in conventional C-OFDR. The beat signal obtained from the MI, b(t), corresponding to the reflection at the round trip.

3.3 Frequency division multiplexing coherent OTDR for submarine cable monitoring

A. Issues with construction and maintenance of submarine optical fiber cables

As mentioned in Section 2.3, the C-OTDR is used for fault location and characterization in long-haul submarine applications. In the repeatered system shown in Fig. 3, repeater spans occasionally exceed 100 km. There is a problem in that the dynamic range (DR) is sometimes insufficient, because the peak power of the probe pulse from the repeater is restricted by the output power of the EDFA in the repeaters.

To achieve a good signal-to-noise ratio in reflectometry traces, a large number of measurements must be performed for averaging. Manufactured submarine transmission lines (including optical cables, repeaters, etc.) are examined under several circumstances, for example during acceptance inspection, shipping, final inspection after laying and when identifying a fiber fault during operation. There has been a need for a more sensitive reflectometry technique to shorten the measurement time.

An approach employing a coded pulse train has been reported as a technique for improving the sensitivity while retaining the same spatial resolution [27, 28]. A pulse train that has an orthogonal code with a time shift provides theoretically the distributed reflectivity along the optical fiber by auto-correlation. However, this approach may induce large crosstalk effects owing to insufficient side lobe suppression since it is not easy for repeatered systems that incorporate a large gain exceeding several decades of decibels in optical amplifiers. On the other hand, another approach has been reported in which the optical frequency of the probe pulse is encoded [29]. We used the latter approach as a basis, since it is easy to suppress side lobes by employing a sufficient narrow band laser as a light source, and we developed a new C-OTDR technique. This approach requires a broad receiver bandwidth compared with the code pulse train technique, but it is easy to obtain the bandwidth with a recently developed high-speed balanced detector and an analog to digital (A/D) converter with several hundreds of MHz. We call this C-OTDR approach

frequency division multiplexing OTDR (FDM-OTDR).

B. High sensitivity measurement by FDM-OTDR [30]

FDM-OTDR. A probe pulse with multiple frequencies is launched into the FUT. Each frequency component is serially arranged in the time domain thus avoiding both a peak power increase and a nonlinear interaction as a result of four wave mixing. They are detected by a single photodetector, which is responsible for the total test light pulse bandwidth, and digitized by an A/D converter. The digitized backscattered signals can be separated into individual frequency components with a fast Fourier transform (FFT). As a result, multiple OTDR traces measured at different frequencies can be obtained simultaneously. This means that several C-OTDR traces can be obtained within a single iteration of the measurement . Hence, the DR per iteration can be improved by using this scheme. The round-trip DR improvement in the FDM-OTDR is given by FDM 10lg N (dB) (7) where NFDM is the number of frequencies in the probe pulse. Frequency demultiplexing is performed based on software processing, which indicates that no specific hardware is needed for demultiplexing and it is not much more complicated than the conventional C-OTDR.

IV. CONCLUSIONS

Recent research and development in relation to optical fiber monitoring were reviewed. The optical reflectometry is a promising technology that enables operators to maintain a large number of facilities. There is no doubt that simple OTDR (or C-OTDR) approaches play a role as the main technology for current optical fiber monitoring in communication systems. However, the diagnosing problems in communication systems will become more multifaceted as the systems progress and will require different functions related to optical access, trunk and submarine configurations and applications. Further research and development of optical fiber monitoring technologies are expected with a view to realizing highly reliable optical services.

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