Simplified optical correlation-domain reflectometry using polymer fiber

Neisei Hayashi[a], Makoto Shizuka, Kazunari Minakawa, Yosuke Mizuno, and Kentaro Nakamura
Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama 226–8503, Japan
a) *hayashi@sonic.pi.titech.ac.jp*

Abstract: We develop a simplified configuration of optical correlation- (or coherence-) domain reflectometry (OCDR) using a polymer optical fiber (POF). The conventional reference light path is removed by using as reference light the Fresnel-reflected light caused at the interface between a silica single-mode fiber and the POF. We demonstrate its basic operation and investigate the dependences of the spatial resolution and signal-to-noise ratio (SNR) on the sweep time of the laser modulation frequency. The optimal sweep time is found to be 30 ms (corresponding to a repetition rate of 33 Hz), at which both the resolution and SNR are maintained at high values.

Keywords: polymer optical fibers, optical correlation-domain reflectometry, Fresnel reflection
Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Detection of bad connections and splices in optical fiber networks has recently become extremely important. One of the most widely used techniques is fiber-optic reflectometry based on Fresnel reflection. Two of its major configurations are optical time-domain reflectometry (OTDR) [1, 2, 3, 4, 5] and optical frequency-domain reflectometry (OFDR) [6, 7, 8, 9, 10]. OTDR, however, generally suffers from its insufficient spatial resolution and relatively long measurement time, whereas OFDR is susceptible to phase fluctuations caused by environmental disturbance. One promising technique for mitigating these problems is optical correlation (or coherence)-domain reflectometry (OCDR) [11, 12, 13, 14, 15, 16, 17, 18, 19, 20] using synthesized optical coherence function (SOCF) [18], which operates based on optical correlation control through modulated optical frequency of the laser output. Two methods have been reported to implement the frequency

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modulation: sinusoidal modulation [13, 14, 15] and stepwise modulation [16, 17, 18]. The latter includes the use of an optical frequency comb [19, 20], which improves the measurement stability. Of these two methods, sinusoidal modulation can be implemented with the higher cost efficiency.

In a standard OCDR-SOCF system [13, 14, 15, 16, 17, 18, 19, 20], the Fresnel spectrum is shifted by several tens of megahertz by optical heterodyne detection using an acousto-optic modulator (AOM) to avoid the overlap of low-frequency noise of the electrical devices. To perform electrical signal processing in the frequency range near direct current (DC), and thus to reduce the cost of the relevant devices, we have recently succeeded in excluding the optical heterodyne detection (i.e. without the use of an AOM) by exploiting the foot of the Fresnel spectrum [21]. High-speed operation has also been demonstrated by tracking a moving loss point. Further simplification of this AOM-free configuration will boost the convenience in practical use.

In the meantime, fibers under test (FUTs) used so far were basically silica-based single-mode fibers (SMFs). However, for the past decade, polymer optical fibers (POFs) have emerged as candidate media for next-generation optical home networks due to their various advantages, such as high flexibility (endurable for several tens of percent of strain), low-cost connection, ease of handling, and high safety [22, 23]. By exploiting these merits, POFs have been already used to implement some optical reflectometers [24, 25], but not yet employed in OCDR systems.

In this work, by the use of a POF, we further simplify the AOM-free OCDR-SOCF. By using as reference light the Fresnel light reflected at the interface between a silica SMF and the POF, the conventional reference light path can be removed, leading to the further simplified setup. After demonstrating a distributed reflectivity measurement, we investigate the dependences of the spatial resolution and the signal-to-noise ratio (SNR) on the sweep time of the laser modulation frequency. A repetition rate of 33 Hz is found to be optimal to accomplish a high spatial resolution and a high SNR simultaneously.

2 Principle

The experimental setup of standard OCDR-SOCF including an AOM [15] is depicted in Fig. 1(a). The laser output is divided into two; one is used as incident light and the other is used as reference light. After passing though the AOM for frequency downshift by several tens of megahertz, the incident light is injected into an FUT (silica SMF), the open end of which is angled cut to suppress the Fresnel reflection. The reflected light is heterodyned with the reference light to generate an optical beat signal, which is converted into an electrical signal using a photo detector (PD) and is then monitored using an electrical spectrum analyzer (ESA). The influence of the low-frequency noise of the PD and ESA can be mitigated by using the heterodyne detection. To measure the reflected light in a distributed manner, the optical frequency of the laser output is sinusoidally modulated to form a so-called "correlation peak" in the FUT [18]. By controlling the modulation frequency, the location of the correlation peak can be scanned along the FUT, which enables distributed reflectivity measurement. As a sinusoidal waveform is a

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periodical function, the correlation peaks also appear periodically along the FUT, and therefore their interval determines the measurement range D, which is given by

$$D = \frac{c}{2nf_m}, \tag{1}$$

where c is the optical velocity in vacuum, n is the refractive index of the fiber core, and f_m is the modulation frequency. As for the spatial resolution Δz, it is defined as a 3-dB linewidth of the correlation peak, which is theoretically given by [26]

$$\Delta z \cong \frac{0.76c}{\pi n \Delta f}, \tag{2}$$

where Δf is the modulation amplitude.

Subsequently, a recently developed setup of the OCDR-SOCF without the use of the AOM is shown in Fig. 1(b). This configuration works properly because the Fresnel spectrum in reality has some non-negligible bandwidth (determined by the laser bandwidth); the foot of the Fresnel spectrum, which is not overlapped by the low-frequency noise of the PD and ESA, is used for reflectivity sensing [21]. The measurement range D and the spatial resolution Δz are given as the same expressions as Eq. (1) and Eq. (2), respectively [21].

Finally, a further simplified setup of the AOM-free OCDR is depicted in Fig. 1(c); a POF with its open end angled cut is used as the FUT. At the butt-coupled interface between a silica SMF ($n \sim 1.46$; the pigtail of an optical circulator) and the POF ($n \sim 1.35$; perfluorinated, as detailed in the next section), relatively high-power Fresnel-reflected light (theoretical reflectivity ~0.2%) is generated. We utilize this Fresnel light as new reference light instead of the conventional reference light, and thus the conventional reference light path can be removed from the system. Note that similar implementation has been reported in a Brillouin-based OCDR system [25, 27]. The 0-th correlation peak, i.e. the zero-optical-path-difference point, is always located at the SMF-to-POF interface, and

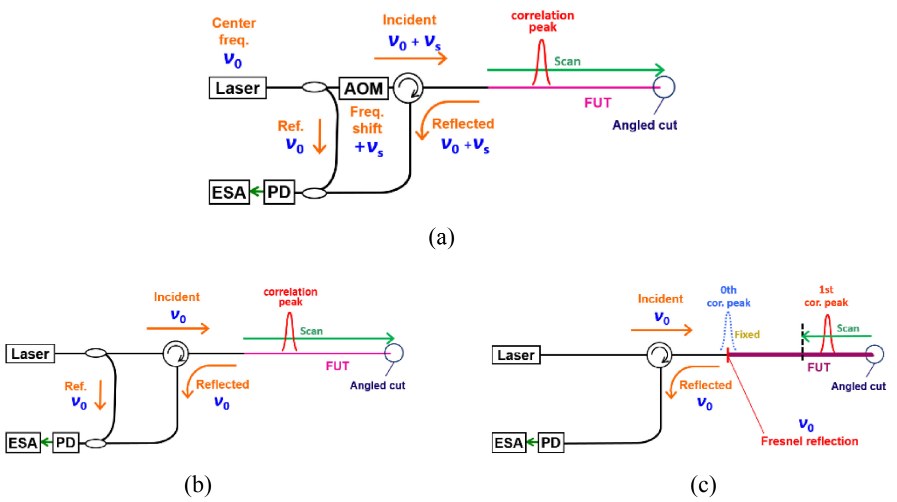

Fig. 1. Schematic experimental setups of (a) standard optical correlation-domain reflectometry (OCDR) [15], (b) acousto-optic modulator (AOM)-free OCDR [21], and (c) further simplified AOM-free OCDR using a polymer optical fiber (POF). ESA, electrical spectrum analyzer; FUT, fiber under test; PD, photo detector.

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the 1st correlation peak is used for distributed measurement. Note that when the 1st peak reaches the midpoint of the POF, the 2nd peak starts to enter the POF at the open end. Thus, the measurement range is limited to the distal half of the POF length rather than Eq. (1).

3 Experimental setup

The actual experimental setup of further simplified AOM-free OCDR using a POF as an FUT is schematically shown in Fig. 2(a). All the optical paths except the FUT were composed of silica SMFs. A laser diode at 1.55 µm with a 3-dB bandwidth of ~1 MHz was used as a continuous-wave light source. The laser output was polarization-scrambled, amplified to ~16 dBm using an erbium-doped fiber amplifier (EDFA), and was injected into the FUT via an optical circulator. The reflected light from the FUT was amplified to ~3 dBm using another EDFA. The optical beat signal of this reflected light and the Fresnel-reflected light was converted into an electrical signal using a PD, and was sent to an ESA. To achieve high-speed operation, the spectral power at 3 MHz (selected so that the SNR becomes maximal [21]) was continuously output from the analog terminal of the ESA to an oscilloscope (OSC). The resolution bandwidth and the video bandwidth of the ESA were set to 300 kHz and 1 kHz, respectively.

The structure of the FUT is shown in Fig. 2(b). A 1.0-m-long pigtail of the circulator was connected to 10.0-m-, 2.9-m-, 2.9-m-, 2.0-m-, and 2.2-m-long POFs sequentially using SC/PC connectors; the distal end of the FUT was kept open (angled cut). Note that the POFs used here were perfluorinated graded-index POFs [28]. The core and cladding layers, composed of doped and undoped polyperfluorobutenylvinyl ether, have diameters of 50 µm and 70 µm, respectively. The refractive index at the center of the core is 1.356, the numerical aperture is 0.185, and the propagation loss at 1.55 µm is ~250 dB/km. The polycarbonate reinforcement overcladding layer (diameter: 490 µm) reduces micro-bending loss.

The laser output frequency was sinusoidally modulated by direct modulation of the driving current [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. The modulation frequency f_{m} was swept from 5.52 MHz to 11.05 MHz with a repetition rate of 10 Hz. The measurement range D was half the POF length, i.e. 10.0 m. The modulation amplitude Δf was fixed at 0.75 GHz, resulting in the theoretical spatial resolution Δz of approximately 71.5 mm (refer to Eq. (2)). The room temperature was 24 °C.

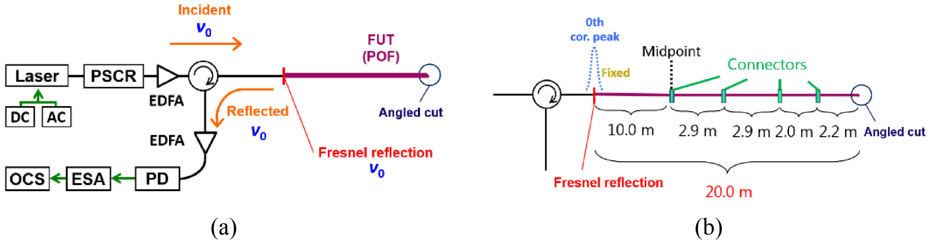

Fig. 2. (a) Actual experimental setup of further simplified AOM-free OCDR using a POF, and (b) the structure of the fiber under test (FUT). AC, alternating current; DC, direct current; EDFA, erbium-doped fiber amplifier; OSC, oscilloscope; PSCR, polarization scrambler.

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4 Experimental results

First, we confirmed the basic operation of the system by measuring the reflectivity distribution along the FUT. The sweep time of the modulation frequency was set to 30 ms, and no averaging was performed. The result is shown in Fig. 3; note that the vertical axis is a Fresnel-reflected power. The relative position was here defined as the distance from the open end of the FUT. Three clear peaks were observed at the relative positions of 2.2, 4.2, and 7.1 m, which correspond to the locations of the connectors. The peak power corresponds to the actual reflectivity of each connector. The 3-dB bandwidth of the maximal peak observed at the relative position of 4.2 m, which can be regarded as the spatial resolution, was approximately 0.11 m; this value was in moderate agreement with the theory (note that the derivation of Eq. (2) includes some mathematical approximations).

Next, the effects of the sweep time on the spatial resolution and the SNR were investigated. In this experiment, the SNR was defined as the difference between the maximal peak power and the lowest power of the noise floor (at the relative position of 8.9 m in Fig. 3); this definition is the same as that in Ref. [15]. Fig. 4(a) shows the spatial resolution plotted as a function of the sweep time. The resolution grew higher with increasing sweep time, and it became almost constant when the sweep time was longer than ~30 ms. Fig. 4(b) shows the SNR dependence on the sweep time. The SNR increased with increasing sweep time, and also became almost constant when the sweep time was longer than ~30 ms, considering the SNR fluctuations of +/− 1 dB. Thus, a ~30-ms sweep time, corresponding to a repetition rate of ~33 Hz, was found to be optimal in this condition.

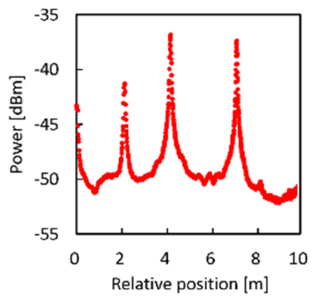

Fig. 3. Measured distribution of the Fresnel-reflected power.

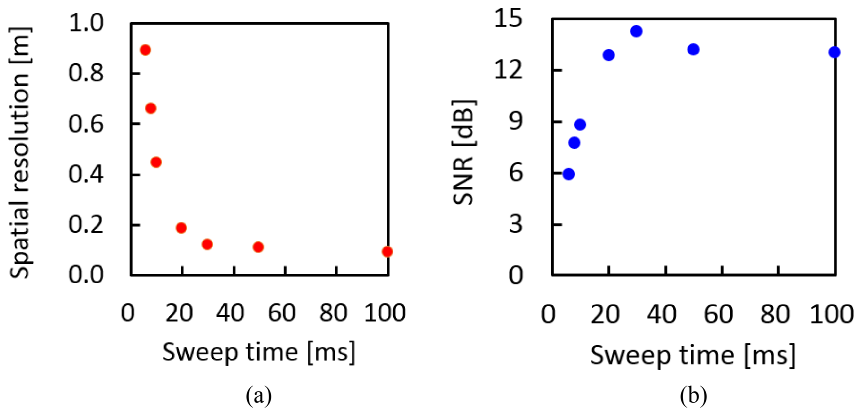

Fig. 4. Measured sweep-time dependences of (a) the spatial resolution and (b) the signal-to-noise ratio (SNR).

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5 Conclusion

By use of a POF, a standard AOM-free OCDR-SOCF system was further simplified. By using as reference light the Fresnel light reflected at the SMF-to-POF interface, the conventional reference light path was removed. We confirmed the distributed reflectivity measurement capability, and investigated the effects of the sweep time of the laser modulation, i.e. the repetition rate, on the spatial resolution and the SNR of the system. A repetition rate of 33 Hz was found to be optimal to achieve a high spatial resolution and a high SNR simultaneously. We expect that our further simplified POF-based AOM-free OCDR-SOCF system will be one of the most promising techniques for cost-effective distributed reflectivity sensing in future.

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