We develop a simplified configuration for optical correlation-domain reflectometry (OCDR) without an explicit reference path. Instead, the Fresnel-reflected light generated at the distal open end of the sensing fiber is exploited as a reference light. After the fundamental demonstration, the optimal incident power is found to be approximately 8 dBm. We also show that the loss near the distal end should not be applied, unlike in the case of Brillouin-based OCDR.

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1. INTRODUCTION

Fiber-optic reflectometry is a fundamental technique for implementing multiplexed and distributed sensing systems [1–8], and its various configurations have been developed to detect a variety of physical parameters, such as strain [2–4], temperature [3–6], pressure [7], and humidity [8]. Among these various configurations, in order to detect bad connections (or splices) and other reflection points along fibers under test (FUTs) in a distributed manner, three types of fiber-optic reflectometry based on Fresnel reflection have been developed: optical time-domain reflectometry (OTDR) [9–13], optical frequency-domain reflectometry (OFDR) [14–18], and optical correlation (or coherence)-domain reflectometry (OCDR) [19–28]. It has been reported that OTDR commonly suffers from a relatively low spatial resolution and a low sampling rate, while OFDR generally suffers from phase fluctuations caused by environmental disturbances. Thus, here we focus on OCDR, which can mitigate these shortcomings.

OCDR operates by exploiting a synthesized optical coherence function (SOCF) [26]—i.e., by controlling the correlation of propagating light beams through optical frequency modulation. The modulation methods can be broken into two categories: sinusoidal modulation [21–23] and stepwise modulation [24–26] (including frequency-comb-based modulation [27,28]). As the latter approach requires accurate frequency adjustment and/or frequency-comb generation, sinusoidal modulation is more cost-efficient [21–23]. In a standard SOCF-OCDR system [21–28], an optical frequency shifter such as an acousto-optic modulator (AOM) is utilized so that the heterodyned Fresnel spectrum is shifted from DC by several dozen megahertz; otherwise, the Fresnel reflection spectrum to be detected overlaps with the low-frequency noise of the electrical devices.

Additionally, in order to reduce the cost of the system, we have recently developed a new SOCF-OCDR configuration without using an AOM [29]. By exploiting the foot of the Fresnel reflection spectrum, a sufficiently high signal-to-noise ratio (SNR) was obtained. However, in both the standard and simplified SOCF-OCDR configurations mentioned above, two optical paths—the incident optical path including an FUT and the reference optical path for optical interference—were required. Removing the reference path will further simplify the system and boost its practical convenience.

By using a polymer optical fiber (POF) as an FUT, we have already demonstrated SOCF-OCDR operations without an explicit reference path [30]. In this case, the Fresnel-reflected light generated at the boundary between the POF and a silica single-mode fiber (SMF; a pigtail of an optical circulator) was used as a reference light. However, when the FUT is composed not of a POF but of silica SMF, Fresnel-reflected light is not generated at the boundary of the two silica SMFs, which makes it difficult for us to demonstrate the similar SOCF-OCDR operations.

In this work, we develop a simplified configuration of AOM-free SOCF-OCDR without an explicit reference path when standard silica SMF is used as an FUT. Instead, the Fresnel-reflected light generated at the distal open end of the FUT is exploited as a reference light. In addition to demonstrating the basic operation of this approach, we investigate the optimal incident power and the influence of the loss near the distal end on the measured results.
2. PRINCIPLE AND EXPERIMENTAL SETUP

Figure 1 depicts the experimental setup of the AOM-free SOCF-OCDR without a reference path, which is extremely simple compared to previous configurations [21–29]. The laser output at 1550 nm was amplified using an erbium-doped fiber amplifier (EDFA) and was injected into a FUT composed of sequentially connected multiple silica SMFs (detailed below in this section). The reflected light, which contained the optical beat signal between the light beams reflected at the SMF-to-SMF boundaries and the light beam Fresnel-reflected at the distal open end of the FUT (~4% reflectivity), was guided to a photodetector (note that some structural analogy can be found in optical coherence tomography [31]). The beat signal was then converted into an electrical signal and input to an electrical spectrum analyzer (ESA). By using the ESA as an electrical narrow bandpass filter, the electrical spectral power at 2 MHz (at which a maximal SNR can be obtained [29]) was selectively transmitted to an oscilloscope. The resolution bandwidth and the video bandwidth of the ESA were set to 300 kHz and 1 kHz, respectively.

To perform distributed reflectivity (or reflection power) measurements, the output frequency of the laser was sinusoidally modulated by directly modulating the driving current, leading to the formation of a correlation peak in the FUT [26] (here we denote the modulation frequency and amplitude of the optical frequency by \( f_m \) and \( \Delta f \), respectively). The light reflected at a specific position along the FUT can be selectively observed using the correlation peak. By sweeping the modulation frequency, the correlation peak is scanned along the FUT, and in this manner the reflectivity distribution can be obtained. In a conventional SOCF-OCDR system involving a reference path (either with or without an AOM), sinusoidal frequency modulation generates multiple correlation peaks periodically. The measurement range \( D \) is then given by the spacing between the correlation peaks as follows [32],

\[
D = \frac{c}{2n f_m},
\]

where \( c \) is the velocity of light in a vacuum, and \( n \) is the refractive index of the fiber core. The spatial resolution \( \Delta z \) (which equals the 3 dB linewidth of the correlation peak) is theoretically given by [32]

\[
\Delta z \cong \frac{0.76c}{\pi n \Delta f}.
\]

This is because in this configuration, the 0th correlation peak—i.e., the zero-optical-path-difference point—is constantly located at the distal open end of the FUT, and the first correlation peak is utilized for distributed measurement. When the first peak reaches the midpoint of the FUT, the second peak starts to enter the FUT at the optical circulator. Note that a similar configuration has been implemented in a Brillouin-based OCDR system [33]. Although the spatial resolution of this simplified Brillouin OCDR is a function of the sensing position, that of the SOCF-OCDR without a reference path is not dependent on the sensing position.

The detailed structure of the FUT is shown in Fig. 2. A 1.0 m long pigtail (silica SMF) of the circulator was sequentially connected to 2.9, 3.0, 7.0, 3.0, 3.0, and 2.9 m long silica SMFs using fiber-channel/physical-contact (FC/PC) or fiber-channel/angled-physical-contact (FC/APC) connectors. The distal PC end of the FUT was kept open. The modulation frequency \( f_m \) was swept from 4.67 to 9.34 MHz with a repetition rate of 33 Hz, which corresponds to the measurement range of \( d = 0–10.9 \) m (where \( d \) was defined as the length between Connector A and the distal end). The modulation amplitude \( \Delta f \) was set to 0.75 GHz (to avoid the damage of the laser), which corresponded to the spatial resolution of 66 mm according to Eq. (2). The range-to-resolution ratio was currently 167, which can be further enhanced by employing a laser specially designed for high-amplitude modulation use, such as a superstructure-grating distributed-Bragg-reflector laser [34,35]. A temporal gating technique [36,37] may be another method for improving the range-to-resolution ratio.

3. EXPERIMENTAL RESULTS

First, the reflection power distributions along the FUT were measured with varying incident power \( P_{in} \) as shown in Fig. 3. When \( P_{in} \) was higher than ~0 dBm, clear peaks corresponding to Connectors B and C were observed at \( d = 2.9 \) and 5.9 m, respectively, which verified the basic operation of this system. However, when \( P_{in} \) was lower than ~0 dBm, the peak corresponding to Connector C was buried by the noise floor.

We then evaluated the \( P_{in} \) dependence of the SNR of each peak, which was defined as the ratio between the reflection power and the noise floor at a certain position. As shown in Fig. 4, as \( P_{in} \) increased, the SNR became maximal and then decreased for both peaks. Under these experimental conditions, the optimal \( P_{in} \) value that yielded the maximal SNR was approximately 8 dBm, irrespective of the connector in question. Another finding is that the measurement was correctly performed with a moderate SNR even when \( P_{in} \) was lower than 0 dBm. This indicates that the EDFA is not required in the
incident path, which is desirable from the standpoint of system simplification.

At this point, we evaluated the influence of the noise caused by the 0th correlation peak. Note that in a Brillouin-based OCDR system without a reference path, some amount of loss must be artificially applied near the distal open end in order to mitigate the influence of the 0th correlation peak, and thus to obtain a sufficiently high SNR [33]. Accordingly, a tunable bending loss was applied to the point 0.1 m away from the distal end. The \( P_{\text{in}} \) value was 8 dBm. The dependence of the measured reflection power distribution on the bending loss is shown in Fig. 5. As the bending loss increased, the power of the two peaks corresponding to Connectors B and C decreased, while new peaks started to grow at \( d = 2.9 \), \( 9 \), and \( 10 \) m, where no connectors existed. These ghost peaks can be explained by the fact that, as the reflection power from the original 0th correlation peak located at the distal end decreases, one of the SMF-to-SMF boundaries with relatively weak reflectivity starts to function as a new 0th correlation peak; in this manner, the multiple reflections among the connectors result in the appearance of the ghost peaks.

Finally, the bending loss dependence of the SNR (the ghost peaks were also included in the SNR measurements) at \( d = 2.9 \), \( 9 \), and \( 10 \) m was measured (Fig. 6). As the bending loss increased, the SNR of the desired peak at \( d = 2.9 \) m decreased, while those of the ghost peaks increased. This result indicates that, unlike in the case of the Brillouin OCDR system that is based on frequency information, we need not (or should not) apply an artificial loss near the open end in the Fresnel OCDR system that is based on power information.

4. CONCLUSION

A simplified SOCF-OCDR configuration without an explicit reference path was developed. As standard silica SMF was used as an FUT, and the Fresnel-reflected light generated at the distal open end of the FUT was exploited as a reference light. Distributed reflection power measurements were demonstrated, and the optimal incident power was found to be approximately 8 dBm. We also showed that the loss near the distal end should not be applied, unlike in the case of

Fig. 3. Measured distributions of reflection power as a function of position for various incident powers.

Fig. 4. Signal-to-noise ratio (SNR) measured as a function of the incident power.

Fig. 5. Measured distributions of reflection power for various bending loss values.

Fig. 6. Signal-to-noise ratio (SNR) measured as a function of the bending loss.
Brillouin-based OCDR. We believe that although our simplified AOM-free SOCF-OCDR system has a disadvantage that its measurement range is limited to the proximal half of the FUT length, it will still be of great use in implementing cost-efficient distributed reflectivity sensors in the future.

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