40 μm Spatial Resolution Optical Frequency Domain Reflectometry at 3 km Based on Relative Distance Measurement to Local Delay Fibre

Tatsuya Okamoto[(1)], Daisuke Iida[(1)], Hiroyuki Oshida[(1)]

[(1)] NTT Access Network Service Systems Laboratories, tatsuya.okamoto.dh@hco.ntt.co.jp

Abstract We demonstrate 40 μm spatial resolution over a few kilometres by optical frequency domain reflectometry (OFDR). The measurement setup overcomes short distance measurement drawback and interrogates distant locations with high resolution. Application of an optical splitter in long-range high-resolution reflectometry is also investigated.

Introduction

An optical fibre reflectometry diagnoses a device under test (DUT) by measuring the backscattered light from the DUT. There is a trade-off between the spatial resolution and the measurement range, where the trade-off defines the measurable size of DUT. Optical time domain reflectometry (OTDR) has a spatial resolution of a few meters over the measurement range of tens of kilometres. It has been applied for fault location of the optical fibre network [1] and structural health monitoring [2]. Optical low-coherence reflectometry (OLCR) has demonstrated a resolution, higher than 100 micro-meters, by utilizing an interference of low-coherence light. However, the measurement range is restricted by the movable length of the local mirror, which is limited to a few meters and is used for a diagnosis for the optical devices, such as the planner waveguide circuit [3]. Some efforts in extending the measurement range have been explored and demonstrated a measurement range of over 10 meters with a spatial resolution, better than 100 μm [4]. Similarly to OLCR, optical frequency domain reflectometry (OFDR) also has a high spatial resolution, better than 100 micro-metres, over tens of meters and is used not only for optical device diagnosis [5], but also sensing applications [6]. The measurement range is restricted by a phase noise of a tuneable laser source and the low phase noise laser has been used for extending the measurement range up to 100 km [7]. The trade-off between the spatial resolution and the measurement range has been an obstacle in realizing an interrogation over large distances with high spatial resolution. Measurements for over a few kilometres with sub 100 μm resolution has not been demonstrated so far.

In this work, we demonstrate a measurement of a location at a distance of 3 km with a 40 μm spatial resolution. Such measurement was performed for the first time to our knowledge. We employ the OFDR setup based on a measurement of relative distance to local fibre length that delays local light [8]. The local delay fibre shifts the reference distance, where the beat frequency between the local and the backscattered light is zero. This allows us to measure the backscattered light from a distant location with a low bandwidth receiver. Moreover, due to the local delay fibre, which provides the same amount of chromatic dispersion as that of the fibre under test (FUT), even when the measurement is for a distant location with a broad frequency-sweeping, the measurement setup compensates for the broadening of the reflection by the chromatic dispersion to realize the theoretical spatial resolution. For one of the applications of the distant location interrogation with high spatial resolution, we also show an identification of the number of connected branches of an optical splitter for optical fibre network management.

High spatial resolution measurement at distant location with local delay fibre

Figure 1 shows a schematic diagram of the measurement setup. The configuration is the same as that of former OFDR, which measures the reflectivity along the absolute distance of the FUT, except it uses the local delay fibre and an optical 90-degree hybrid. Let us consider the interrogation of a distant section of the FUT. The tuneable laser source (TLS) launches a frequency-swept light into the FUT, and the frequency-swept light is backscattered at every location along the FUT. The backscattered light superposes to yield a signal at every location and the beat signal between the delayed local and signal light represents an optical frequency response of the entire FUT to the frequency-swept light.

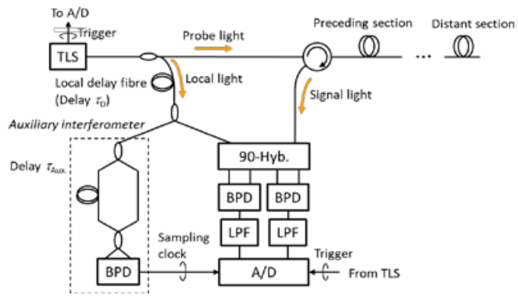

Fig. 1: Schematic diagram of measurement setup. Tunable laser source (TLS), Balanced photodetector (BPD), Optical 90 degree hybrid (90-Hyb.), Low-pass filter (LFP), Analog to digital converter (A/D).

$$\tilde{r}(\nu) = \int r(\tau_\mathrm{R}) \exp[-j2\pi\nu(t)\tau_\mathrm{R}] d\tau_\mathrm{R},$$
$$\tau_\mathrm{R} = \frac{2}{c}\left(z - \frac{L_\mathrm{D}}{2}\right). \qquad (1)$$

Here, $\tilde{r}(\nu)$ is the optical frequency response of the entire FUT, ν is the optical frequency, τ_R is the relative delay, z is the absolute distance of the FUT, L_D is the length of the local delay fibre, c is the speed of light in the fibre, and $r(\tau_\mathrm{R})$ is the reflection coefficient of electrical field of the light, which is related to reflectivity by the square of the absolute value. Note that optical frequency ν is time-dependent, since the optical frequency ν is swept over the time. A sampling clock, obtained with the auxiliary interferometer, realizes an equally-spaced sampling in the optical frequency domain. In this case, the sampling spacing is equal to the free spectral range of the auxiliary interferometer. The setup measures the optical frequency response centring around the distance, which corresponds to the half of the length of the local delay fibre. Since measuring the response centring around the delay fibre, the beat signal consists of a double sided spectrum, where the negative and the positive beat frequencies correspond to the distances before and after the half of length of the local delay fibre, respectively. To discriminate the sign of the beat frequency, an optical 90-degree hybrid is employed for quadrature detection. The low-pass filters (LPFs) prevent aliasing of the signal light from the relative distance, which is larger than a quarter of the imbalance length of the auxiliary interferometer. Changing the local delay fibre, we can measure the optical frequency response at an arbitrary distance of the FUT. The reflectivity at the arbitrary section of the FUT is obtained with the same procedure as the former OFDR, which is a processing for the squared absolute values of Fourier transform of the optical frequency response. Note that the setup does not extend the measurement range but selects the range to be measured with the local delay fibre. The number of resolved points, namely a ratio of the measurement range to the spatial resolution, is doubled by measuring the distance preceding and following the local delay fibre.

In contrast to the current setup, the former OFDR has no local delay fibre, $L_\mathrm{D} = 0$. Thus, the beat signal between the local and signal light in Eq. (1) can be rewritten as follows.

$$\tilde{r}(\nu) = \int r(\tau_\mathrm{A}) \exp[-j2\pi\nu(t)\tau_\mathrm{A}] d\tau_\mathrm{A},$$
$$\tau_\mathrm{A} = \frac{2}{c} z, \qquad (2)$$

where τ_A is the absolute delay given by the FUT. The optical frequency response is measured along the absolute distance$z$. Although the long imbalance length of the auxiliary interferometer could be used for interrogation of a distant location, the sampling clock, provided by the interferometer, would not be spaced equally in the optical frequency domain because of a short coherence length of the tuneable laser source, which leads to an inaccurate measurement for the optical frequency response of the FUT as well as a degradation of the spatial resolution. On the other hand, in the relative distance measurement setup, the length of the local delay fibre selects a distance range and allows us to employ the imbalance length of the auxiliary interferometer, which shorter than the coherence length of the TLS, even when a distant location is measured.

Experiment

We adopted a single mode fibre bobbin with a length of 3 km as a FUT and measured the resulting Fresnel reflection. The TLS launched a frequency-swept light, the bandwidth of which was 20 nm with a sweeping speed of a 200 nm/s, and a theoretical spatial resolution, given by the frequency sweeping bandwidth, was 40 μm. A local delay fibre of 6 km, as determined by the OTDR, was employed to interrogate a far end section of the FUT. An imbalance length of the auxiliary interferometer was 200 m, which corresponded to the FSR of 1 MHz. The cut-off frequency of the LPFs was 5 MHz, which corresponds to the relative distance of 20 m.

The measurement result for the reflectivity distribution of the far end section is shown in Figure 2, where the relative distance is converted to the absolute distance by Eq. (1). The measured reflectivity distribution clearly shows the Fresnel reflection at the absolute distance of 3017 m and this result coincides with the FUT to be measured. The Fresnel reflection,

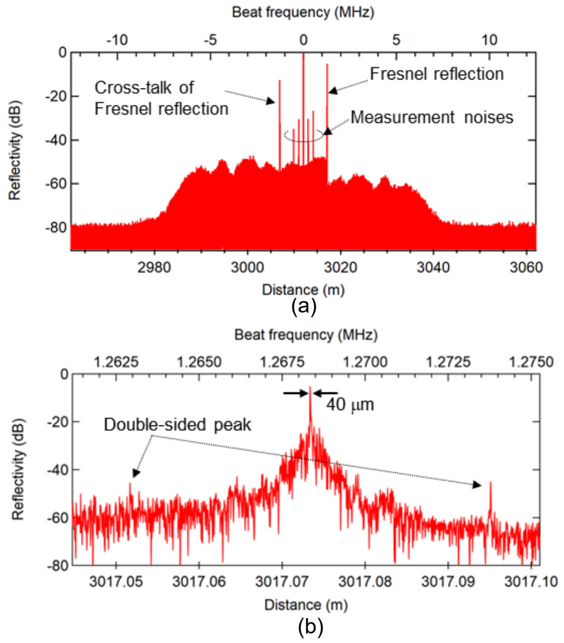

Fig. 2: Reflectivity distribution of (a) far end of the 3 km-long fibre bobbin and (b) magnified Fresnel reflection.

measured with the employed TLS, has a 3-dB width of 40 μm and the symmetric double-sided peaks are smaller than the main peak by about 40 dB. The beat frequency rejection, which is higher than 5 MHz, by the LPFs eliminates the signal light from the relative distance larger than 20 m. This corresponds to an absolute distance less than 2992 m and the noise floor of the measurement setup can then be observed in absolute distance of 3040 m. Several reflection peaks around the low beat frequency, that range from -0.5 to 0.5 MHz, arise from the measurement and can be observed when no FUT is connected to the measurement setup. The reflectivity beyond the location of the Fresnel reflection is a crosstalk of the symmetric negative beat frequency region. This is due to the discrimination imperfection of the sign of the beat frequency by the optical 90-degree hybrid. The reflection at 3007 m is also observed as a crosstalk of the Fresnel reflection at the end of the FUT. The result demonstrates the validity of the method, capable of measuring the reflectivity at a distant location with high spatial resolution.

A distant location reflectometry with a spatial resolution narrower than 100 μm allows unprecedented performance and offers a fine diagnosis for an optical device at a distant location. Here, we demonstrate one application, which is useful for an optical fibre network management. A passive optical network employs an optical splitter at an intermediate location of the fibre to effectively distribute optical fibres to subscribers. The proposed technique realizes an optical diagnosis from the central office, which reveals the usage status of

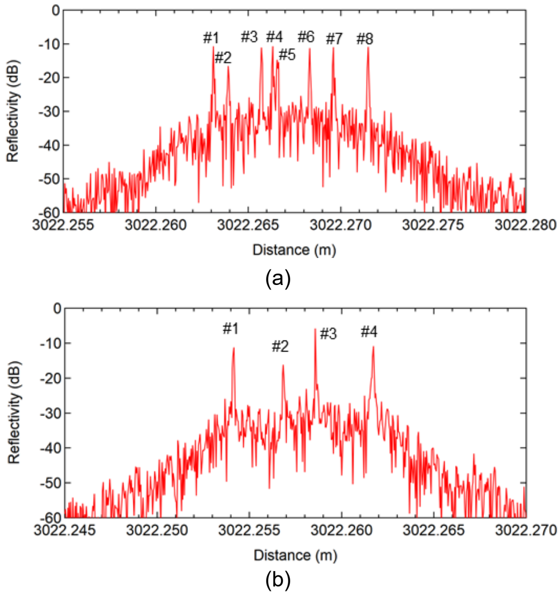

Fig. 3: (a) Fresnel reflections from 8 branches of the optical splitter at a distance of 3 km and (b) Fresnel reflections from an optical splitter with 4 connected branches.

the optical splitter. In the demonstration setup, an optical splitter with 8 branches is located at the end of a 3 km-long fibre spool. The fine diagnosis for the optical splitter reveals the number of Fresnel reflections caused by the open branches, which are not in use. Figure 3 shows the reflectivity distributions around the splitter for all branches, which are not used, and 4 branches, which are used. Measurement results for all open branches show 8 Fresnel reflection peaks within the length of 1 cm, and the results for the 4 used branches show 4 reflection peaks at the splitter location, which means that the number of connected branches is 4. The fine spatial resolution enables us to count the number of open branches to identify the splitter usage.

Conclusions

We have demonstrated an OFDR technique with a 40 μm spatial resolution for a location at a distance of 3 km by employing a relative distance measurement. In this case, a delay fibre for local light selects a measurement range along the fibre and an optical 90-degree hybrid distinguishes between the backscattered light from the distance preceding and following the local delay fibre. The technique can be applied in the OFDR interrogation of an optical device at a distant location. As an example of the distant location interrogation, we have verified the splitter usage by counting the number of Fresnel reflections of open branches.

References

[1] D. Derickson, *Fiber Optic Test and Measurement*, NJ: Prentice Hall, 1998.

[2] J. M. López-Higuera *et al*., “Fiber optic sensors in structural health monitoring”, *IEEE J. Lightw. Technol*., vol. 29, no. 4, pp. 587–608, Feb. 2011.

[3] Y. J. Rao, D. A. Jackson, “Recent progress in fiber optic low-coherence interferometry”, *Meas. Sci. Technol.*, vol. 7, no. 7, pp. 981-999, Apr. 1996.

[4] D. M. Baney and W. V. Sorin, “Extended-range optical low-coherence reflectometry using a recirculating delay technique”, *IEE Photon. Technol. Lett.*, vol. 5, no. 9, pp. 1109-1112, 1993.

[5] B. J. Soller *et al.*, “High resolution optical frequency domain reflectometry for characterization of components and assemblies”, *Opt. Exp.*, vol. 13, no. 2, pp. 666-674, Jan. 2005.

[6] D. P. Zhou *et al.*, “Distributed vibration sensing with time-resolved optical frequency-domain reflectometry”, *Opt. Exp.*, vol. 20, no. 12, pp. 13138–13145, Jun. 2012.

[7] J. Geng, et al., “Narrow linewidth fiber laser for 100-km optical frequency domain reflectometry”, *IEEE Photon. Technol. Lett.*, vol. 17, no. 9, pp. 1827-1829, Sep. 2005.

[8] T. Okamoto et al., “Identification of sagging aerial cable section by distributed vibration sensing based on OFDR”, in Proc. OFC2019, paper Th2A.26.