Novel optical frequency domain reflectometry with measurement range beyond laser coherence length realized using concatenatively generated reference signal

Xinyu Fan and Fumihiko Ito
NTT Access Network Service Systems Laboratories, NTT Corporation.
1-7-1 Hanabatake, Tsukuba, Ibaraki 305-0805, Japan
Telephone: +81-29-868-6119; Fax: +81-29-868-6126; Email:fan@ansl.ntt.co.jp

Abstract: We have developed a novel optical frequency domain reflectometry (OFDR) technique with a measurement range beyond the laser coherence length by using concatenatively generated reference signal from an auxiliary interferometer.

OCIS codes: (060.2300) Fiber measurements; (120.3180) Interferometry

Optical frequency domain reflectometry (OFDR) shows promise as a powerful tool for the maintenance of optical access networks. For this application, the most important parameters are spatial resolution and measurement range. To obtain a narrow spatial resolution together with a long measurement range, we need a laser with both a broad tunable range and a narrow linewidth to give us a long coherence length. Nowadays, laser diodes (LD) are commercially available that have a broad tunable wavelength range, and a spatial resolution of 22 μm [1] has been realized. To extend the measurement range to several kilometers while maintaining a narrow spatial resolution, we must solve the problem of laser coherence length limitation. In this presentation, we will propose a novel OFDR with a measurement range greater than the laser coherence length and demonstrate our proposal experimentally.

In OFDR, the electric field of a tunable LD can be written as

$$E(t) = A\exp\{j[2\pi f(t)t + \theta(t)]\} = A\exp[j\Phi(t)], \tag{1}$$

where A is a constant amplitude, $f(t)$ the swept optical frequency of an LD, $\theta(t)$ is a random phase, and $\Phi(t)$ is the gross time-varying phase. When the field meets a τ-delayed field, the beat signal is

$$I = \left|E(t) + E(t-\tau)\right|^2 \propto \cos[\Phi(t) - \Phi(t-\tau)]\,. \tag{2}$$

For recent high-resolution OFDR systems [1], an auxiliary interferometer is incorporated into the main interferometer to generate a reference signal, which is used as a trigger for sampling the main signal to compensate for the frequency sweeping nonlinearity. Owing to the double-pass nature of the measurement interferometer, the compensation optimally works at a distance of $\tau c/2n$ (c is the speed of light and n is the refractive index of the FUT), and does not work for an FUT of double the length or longer.

The system configuration for a measurement range beyond the coherence length is depicted in Fig.1. Both the data from the main interferometer containing FUT, and the auxiliary interferometer are acquired with A/D converters. These data are sent to a computer for the numerical compensation process. The auxiliary interferometer provides the reference signal,

$$X_1(t) = \Phi(t) - \Phi(t-\tau_c)\,, \tag{3}$$

which is used for the compensation at a distance around $\tau_c c/2n$ in FUT (τ_c is the laser coherence time), half of coherence length L_c in FUT, in conventional OFDRs. Our idea for expanding the measurement range is to use a novel reference signal defined by

$$X_N(t) = \Phi(t) - \Phi(t-N\tau_c)\,, \tag{4}$$

for compensating the measurement section around $NL_c/2$ (N: integer). The above defined reference signal can be numerically obtained from the original reference signal by

$$X_N(t) = X_1(t) + X_1(t-\tau_c) + X_1(t-2\tau_c) + \cdots + X_1(t-N\tau_c)\,. \tag{5}$$

The term "concatenatively generated" in the title originates from this process. Note that although the compensation process is necessary for every section with a length of $L_c/2$, the required data acquisition is only one time. Also note that the required electrical bandwidth of acquiring main data depends on the farthest distance of $NL_c/2$.

In Fig.1, the light source is a New Focus 6328 tunable LD. The coherence time of the LD was compatible for ~1 km length of optical fiber within the time scale of interest. Thus, we selected 1 km as the length of the delay fiber in the auxiliary interferometer. The frequency sweep rate was set at 100 GHz/s and the full swept frequency range

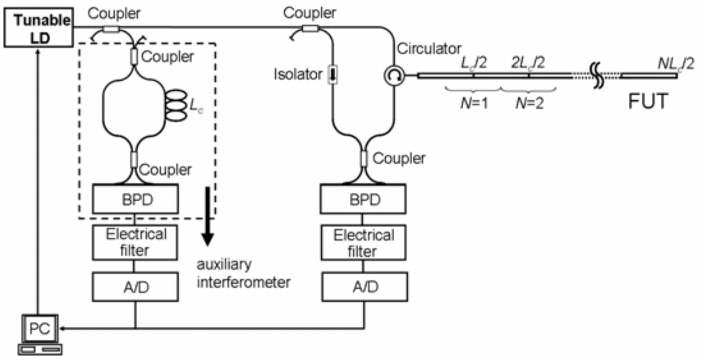


Fig. 1. Experimental setup. L_c, delay fiber with a distance of coherence length; BPD, balanced photodetector; PC, personal computer; FUT, fiber under test.

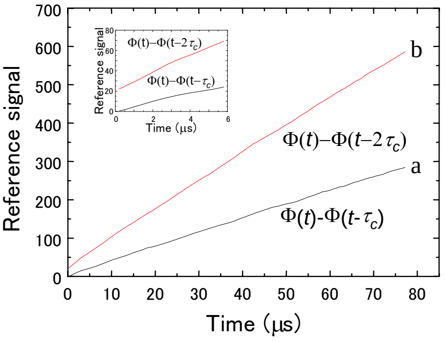
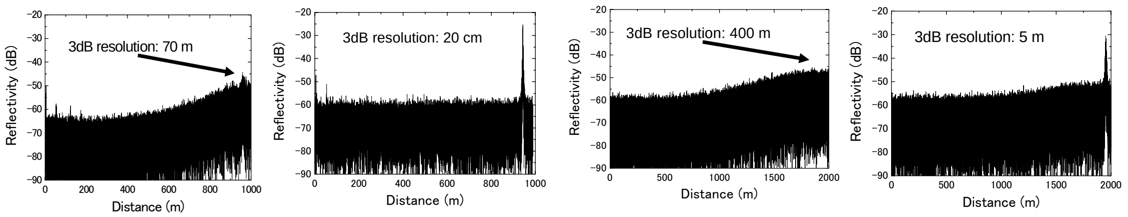


Fig. 2. Reference signal. (a) Original reference signal $\Phi(t)-\Phi(t-\tau_c)$; (b) Concatenatively generated reference signal $\Phi(t)-\Phi(t-2\tau_c)$.



(a) (b) (c) (d)

Fig. 3. Measurement results. (a) 1-km FUT (double the length of $L_c/2$, i.e., N=2 in Eq. 5) sampling based on original reference signal; (b) 1-km FUT sampling based on concatenatively generated reference signal; (c) 2-km (four times the length of $L_c/2$, i.e., N=4 in Eq. 5) FUT sampling based on original reference signal; (d) 2-km FUT sampling based on concatenatively generated reference signal.

was 10 GHz, corresponding to a theoretical spatial resolution of 1 cm. The command to start a sweep is sent to the LD from a computer, which is also used for the compensation processing.

Curve a in Fig. 2 shows the reference signal calculated by using the Hilbert transformation method [2]. After using the algorithm of Eq. 5, we reconstructed the reference signal as shown in curve b of Fig. 2, which we used as a reference to sample the main signal for the second section, which is beyond laser coherence length. Figure 3 shows the measurement results. The FUT in Fig. 3(a) and (b) is near 1 km and has a double pass of about 2 km (double the length of $L_c/2$, i.e., N=2 in Eq. 5). Without using the concatenatively generated reference signal but simply compensating for the main signal based on the original reference signal, flat Lorentzian skirt appears in the spectrum because of the incoherent beating, as shown in Fig. 3(a). At this time, the 3 dB resolution is 70 m. After using the concatenatively generated reference signal, Fig. 3(b) shows that the Lorentzian skirt disappears and the spatial resolution improves to 20 cm. We changed the FUT to one with a length of 2 km (N=4 in Eq. 5), and the measurement results for original and concatenatively generated signal-based compensation are shown in Fig. 3(c) and (d), respectively. The 3 dB resolution improved from 400 m to 5 m.

Our measured spatial resolution results are still broader than the theoretical values. We presume that the Hilbert transformation has limited accuracy, which degrades our calculation accuracy. We expect that if we change from a software to a hardware method, for example if we use a 90-degree optical hybrid to obtain the phase information, the spatial resolution would improve further. Another degrading factor might be that our laser has a rather nonlinear sweep rate. As a result, the spectrum of the reference signal is too broad to allow us to select a suitable electric filter, and this influences the accuracy of phase term calculation. We anticipate that combining a CW laser with an external modulator to sweep the optical frequency as a tunable light source will avoid this problem.

In conclusion, we have developed a novel OFDR with a measurement range beyond the laser coherence length by incorporating an auxiliary interferometer, from which the reference signal is reconstructed in every section of the coherence length, to compensate for the broadened beat signal of the measurement interferometer. We have reported a promising way of achieving a reflectometry technique by maintaining a spatial resolution while extending the measurement range to several kilometers.

References

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