High-reflectivity-resolution coherent optical frequency domain reflectometry using optical frequency comb source and tunable delay line

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Abstract: We propose a high-reflectivity-resolution coherent optical frequency domain reflectometry (OFDR) with a novel scheme of delay shift averaging (DSAV) by using an optical frequency comb source and a tunable delay line to suppress the fading noise. We show theoretically and experimentally that the novel DSAV scheme is equivalent, in realizing a high reflectivity resolution, to our previously reported frequency shift averaging (FSAV) of the same number of teeth of the optical frequency comb [1], but does not need the expensive narrow-pass-band tunable optical filter required in the previous scheme. Furthermore, by using this new method in combination with FSAV, better reflectivity-resolution is obtained compared to using only conventional FSAV with a single-wavelength laser source.

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References and links

1. Introduction

Optical reflectometry is a technique for distributed measurement which gives the profile of reflections and backscattering as a function of the position along optical waveguides. Specifically, coherent optical frequency domain reflectometry (OFDR) is a technique of high spatial resolution and high sensitivity [1–5]. The accuracy (reflectivity-resolution) of OFDR, however, is affected by the coherent fading noise which is caused by the Rayleigh scattering...
in the optical waveguide. The fading noise in reflectometry makes it difficult to measure the variation of backscattering level in the waveguide, such as measuring the attenuation and the insertion loss along the waveguide. To measure the reflectivity distribution along optical waveguides accurately, for example, for diagnoses of the fiber to the home (FTTH) network, reflectivity-resolution of 0.1dB is required. To suppress the fading noise, a method called frequency shift averaging (FSAV) has been invented which averages results of a large number of independent reflectometry measurements performed at different lightwave frequencies [6]. To achieve a high reflectivity-resolution, FSAV needs very large frequency variation range for the laser source of the OFDR. For example, to obtain a 0.1-dB reflectivity-resolution for an OFDR of 5-cm spatial resolution, an FSAV of 400-time measurements over 400 GHz range is required by calculation according to [6].

Generally, an OFDR utilizes a highly coherent laser source of high tuning rate (high tuning speed and large continuous tuning range) to obtain narrow spatial resolution. It is difficult for a single wavelength high-speed tunable laser to cover the large frequency variation range required by FSAV. To obtain large available frequency variation range, we developed recently an OFDR using an optical frequency comb source (OFC) and a narrow-pass-band tunable optical filter [7]. This scheme employs the narrow-pass-band tunable filter to select a tooth from the spectrum of the OFC to perform one OFDR measurement, and then repeat this process with a different OFC tooth one by one, and finally average all the OFDR measurement results obtained with different OFC tooth. This method has been demonstrated successful in realizing high reflectivity-resolution. However, the required tunable filter has to have a pass-band narrower than the interval of the tooth of the OFC and have a broad tunable range, and is thus very expensive.

In this paper, we propose a delay shift averaging (DSAV) OFDR by use of an OFC and an optical tunable delay line (TDL) to suppress the fading noise. This novel scheme can use the same available frequency variation range as that in Ref [7], but does not need the expensive narrow-pass-band tunable optical filter. The DSAV scheme is equivalent in fading-noise suppression to an FSAV of the same number of the teeth of OFC. Furthermore, using this new method in combination with the conventional FSAV, better reflectivity-resolution is obtained than using a conventional FSAV with a single-wavelength laser source.

2. Principle

In the basic configuration, the OFDR consists of a tunable laser source (TLS) whose frequency can be swept continuously in time and an optical interferometer comprising a reference path and a measurement path. The fiber under test (FUT) is connected to the measurement path whereas the reference path is used as a local oscillator. The interferences between the reference lightwave from the reference path and reflections/backscattering coming from the FUT are detected, and then a Fourier transform allows the visualization of beat frequencies in the interferences. If the optical frequency of the TLS is swept at a constant rate, beat frequencies are proportional to the optical path differences between the reflections in the FUT and the reference path. Thus, a reflectometry profile is obtained. In OFDR, the spatial resolution $\Delta z$ is given as

$$\Delta z = \frac{c}{2n_{\text{eff}} \Delta F}, \tag{1}$$

where $c$ is the light velocity in vacuum, $n_{\text{eff}}$ the effective refractive index, and $\Delta F$ the continuous frequency sweep span, respectively.

The beat signal between the reference lightwave and the lightwave backscattered at a certain point in the FUT is detected by the balanced photo-detector, and can be expressed as

$$i_s(t) \propto E_s(\tau) \cos(2\pi f\tau), \tag{2}$$

$$f = f_0 + \gamma t, \tag{3}$$
where $\tau$ is the time delay difference between the two lightwaves, $E_s(\tau)$ is the electric field of the lightwave backscattered at the certain point, $f_0$ and $\gamma$ the initial frequency and the frequency sweeping rate of the laser source, respectively. By Fourier transform of Eq. (2), the contribution of the backscattered lightwave from the certain point to the OFDR output is given as

$$E(f_b) = \frac{1}{T} \int_{-T/2}^{T/2} i_i(\tau)e^{-j2\pi f_0 \tau} d\tau = E_s(\tau)e^{j2\pi f_0 \tau} \text{sinc}(\pi f_0 T), \quad (4)$$

where $f_b = \gamma \tau$ is the beat frequency, and $T$ the duration of frequency sweeping of the light source. By approximating the sinc function with a unit rectangular function with a width of $2\delta\tau$ corresponding to the finite spatial resolution $\Delta z$, Eq. (4) is further modified as

$$E(\tau) = \int_{\tau-\delta\tau}^{\tau+\delta\tau} E_s(\tau)e^{j2\pi f_0 \tau} d\tau \approx a(\tau)e^{j2\pi f_0 \tau}, \quad (5)$$

where $a(\tau)$ is a complex amplitude. Equation (5) means that the backscattered lightwave at the point corresponding to differential time delay $\tau = f_0/\gamma$ gives a contribution proportional to $a(\tau)e^{j2\pi f_0 \tau}$ to the OFDR output. Normally, in OFDR square-law processing is employed to obtain the intensity-reflectivity. Therefore, the contribution of the backscattered lightwave intensity to the OFDR output intensity can be expressed by

$$I = |E(\tau)|^2. \quad (6)$$

The experimental setup of the OFDR using an optical frequency comb (OFC) and a TDL is depicted in Fig. 1. The OFC is used as the light source in this OFDR system. The whole spectrum of the OFC source is modulated externally by a single side band modulator (SSBM) to generate a linear frequency sweep. Balanced photo detectors with polarization diversity are used to suppress the polarization variation induced fluctuation. When using an OFC as the light source, for the $n$th tooth of the comb, the contribution of the lightwave backscattered at a certain point in FUT to the output is expressed, similar to Eq. (5), simply by

$$E_n = a_ne^{j2\pi (f_0 + n-1)\Delta f \tau}, \quad (7)$$

where $a_n$ is the complex amplitude, and $\Delta f$ the interval of the comb. Thus, the contribution of the total backscattered lightwave intensity to the OFDR output intensity is expressed as

$$I = |E_1 + E_2 + \cdots + E_N|^2 = \sum_{n=1}^{N} |E_n|^2 + \left[ \sum_{p} \sum_{q=p}^{N} a_p^* a_q \exp{j2\pi (p-q)\Delta f \tau} \right] + C.C. \quad (8)$$

where $N$ is the number of the comb tooth.
In this system, multiple OFDR measurement results obtained at different optical delay, which is set by TDL at the reference path, are averaged to reduce the fading noise. If an optical delay $\Delta \tau$ is added in each measurement incrementally, and $M$ measurement results are averaged, the averaged intensity is given as

$$I_s = M \sum_{n=1}^{N} |E_n|^2 + \left[ \sum_{n=1}^{N} \sum_{p=1}^{M} E_n E_p \exp \{ j2\pi (q-p) \Delta f \Delta \tau \} \right] + C.C. \]$$

$$= M \sum_{n=1}^{N} |E_n|^2 + \left[ \sum_{n=1}^{N} \sum_{p=1}^{M} E_n E_p \exp \{ j2\pi (q-p) \Delta f \Delta \tau \} \right] + C.C. \right)$$

In Eq. (9), Part I means the average of measurement results obtained at different frequencies, which is exactly the result of FSAV [6]. Part II of Eq. (9), on the other hand, is a summation of cross-correlations between components at different frequencies. When $\{ \Delta \tau, M \} = \{ 1/(N\Delta f), N \}$, that means, the average times $M$ is the same as the number of the comb teeth $N$, the delay increment $\Delta \tau$ is equal to the reciprocal number of $N$ times the comb interval $\Delta f$, Part II disappears and only Part I remains. So our proposed DSAV is equivalent to an FSAV in which the number of measurement times is equal to the number of the OFC teeth. Therefore, the DSAV enables suppressing the fading noise.

3. Experiment

The configuration of the OFC source used in this paper is depicted in Fig. 2, which is composed of a fiber laser ((NKT, E15) as the seed laser source, a phase modulator (PM), and an intensity modulator (IM). The flat frequency comb is generated through PM and subsequent IM driven by an external microwave synthesizer [8,9].

Figure 3 shows the spectrum of the generated OFC in this experiment. The OFC interval $\Delta f$ is 9.8 GHz, and the OFC tooth number at the flat part (3-dB flatness) of the envelope is 13. Then the optical delay $\Delta \tau$ and the number of measurement times $M$ are determined as $\{ \Delta \tau, M \} = \{ 7.8 \text{ ps}, 13 \}$. A standard computer-controlled TDL (Optoquest, DLRA) composed of a prism and a translation stage with 400-ps maximum delay range and 0.005-ps delay resolution is employed to implement the tunable delay. The microwave frequency input into the SSBM is swept over the range of 6-8 GHz, sweeping the whole OFC spectrum with a span $\Delta F$ of 2 GHz, which corresponds to a theoretical spatial resolution of 5 cm in OFDR according to Eq. (1).
Figure 4 shows measured distributed reflection profiles of 500-m SMF and an open physical contact (FC/PC) connector. Figure 4(a) is the result without averaging, which was performed with the fiber laser in Fig. 2 directly as the light source, i.e., bypassing the PM and IM. Figure 4(b) is the result obtained using the OFC as the light source and 13-time DSAV with 13 measurements at 7.8-ps delay interval. Compared with Fig. 4(a), it can be seen clearly that the fading noise is suppressed in Fig. 4(b). The obtained reflectivity resolution is 0.57 dB, which is obtained by dividing the standard deviation by the mean value of the reflectivity data over the range of 100–300 m. The experiment value of reflectivity is very close to the theoretical value 0.56 dB as calculated when the FSAV of the same average times and the same frequency interval is performed [6]. This result confirms that the new scheme is equivalent to FSAV enabling reduction of fading noise.

Then, we use this DSAV scheme in combination with conventional FSAV, and compare the result with the case in which only conventional FSAV is performed with a single-wavelength laser. In this experiment, total microwave frequency modulation range is 6–13 GHz for 10-time FSAV, in which 10 OFDR measurements were performed at 10 different central frequencies with a frequency span of 2 GHz (with overlap in the 6–13 GHz range) respectively, corresponding to 2-cm spatial resolution.

Figure 5 shows experimental results with the same FUT as in Fig. 4. Figure 5(a) is the result of 10-time FSAV performed with the fiber laser in Fig. 2 only as the light source, i.e., bypassing the PM and IM. Figure 5(b) is that with proposed DSAV scheme in combination with FSAV. In this experiment, a 13-time DSAV was performed with the OFC light source at a central frequency at first. After that, the central frequency of the OFC is shifted, and another 13-time DSAV was performed. In this way, ten results of 13-time DSAV implemented at different OFC central frequencies were obtained. By averaging these results, a result of 10-time FSAV was obtained. It is clear that our new scheme realized better accuracy (0.31 dB in Fig. 5(b)) than conventional FSAV method (0.87 dB in Fig. 5(a)).
Fig. 4. Measured reflection profiles of 500-m SMF and an open physical contact (FC/PC) connector, (a) without averaging, and (b) with 13-time DSAV.

Fig. 5. Measured reflection profiles of 500-m SMF and an open physical contact (FC/PC) connector, (a) with only 10-time FSAV, and (b) with 13-time DSAV combining with 10-time FSAV.

4. Conclusion

In conclusion, we proposed a novel delay shift averaging OFDR by use of an optical frequency comb source and a tunable delay line. We demonstrated that this scheme enables suppressing the fading noise as the same as the frequency shift averaging method. When combining this new scheme with the frequency shift averaging, we obtained better reflectivity-resolution compared with OFDR with frequency shift averaging using a single-wavelength laser source.