Localization and Quantification of Reflective Events along An Optical Fiber Using A Two-Wavelength TRA

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We propose a novel transmission-reflection analysis (TRA) method for detection and localization of any type of single event occurring along an optical fiber. By analysing the transmitted and reflected/backscattered power of continuous signals, it is possible to monitor the event and to simultaneously quantify its induced insertion and return losses. The proposed scheme utilizes two interrogating wavelengths, which allows the supervision of both reflective and non-reflective events. Our analytical studies have shown that for a 20 km-long single mode fiber, the accuracy of event localization is kept in the range of ±1.0m by applying the proposed approach.

Introduction

Nowadays, optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR) are widely used schemes for fiber monitoring. However, OTDR and OFDR require either time- or frequency-modulated light sources, which makes the methods not very cost-effective. Moreover, some breakthroughs are still required to address certain limitations, e.g., to address limitations on long measurement time (several minutes are normally needed for monitoring a fiber with a length in tens of kilometers with OTDR [1]) and short measurement range (only a few hundred meters for OFDR [2]). In [3], a transmission-reflection analysis (TRA) method is reported, which is based on the measurement of transmitted and backscattered powers and using an un-modulated light source. This method was proposed for the detection and localization of a non-reflective optical event such as bending. However, most optical events in a fiber are reflective such as discontinuities, misalignments, and breaks that can be present in telecommunication networks. In sensing applications, some transducing processes also results in the presence of a reflective event along the sensing fiber [4].

In order to address the aforementioned problems, a novel solution is proposed to localize both non-reflective and reflective optical events by using a two-wavelength TRA (i.e., 2λ-TRA) technique in a single mode fiber.

Operation Principle

The schematic diagram of the proposed 2λ-TRA is shown in Figure 1. Continuous-wave light emitted by a light emitting diode (LED around λ_1) is launched into a single mode fiber through an optical circulator. An optical isolator is implemented to minimize the back reflections from the fiber end. The transmitted signal (P_{T1}) is measured by the powermeter located after the isolator. The integrated Rayleigh-backscattered/reflected power (P_{B1}) is measured by the second powermeter connected to the third end of the circulator. The same measurement is repeated a second time after changing the wavelength of the LED source (λ_2) in order to get the corresponding transmission and backscattered powers (P_{B2} and P_{T2} respectively). The localization process of a reflective event is based on the unique relationship between the powers backscattered (P_{B1} and P_{B2}) and transmitted (P_{T1} and P_{T2}) for a given event location (see Figure 1).

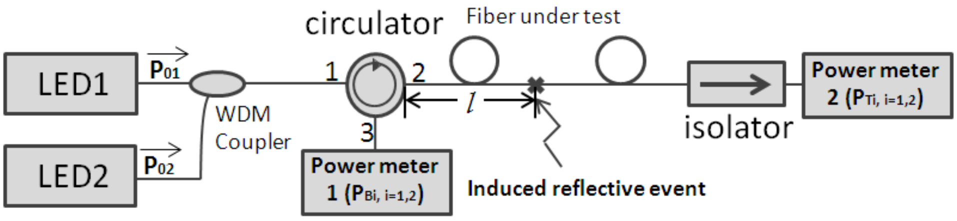

Figure 1: Schematic of the proposed 2λ-TRA technique

Let us consider a fiber with a total length L and an initial transmitted power of the reference undisturbed system:

$$P_{T01} = P_{01} \cdot T_1(L)$$
$$P_{T02} = P_{02} \cdot T_2(L) \quad (1)$$

in which $P_{01(2)}$ is the input power and $T(L)$ is the transmission coefficient associated with the attenuation coefficient α of the fiber, which can be expressed as: $T(\Delta L) = e^{-\alpha\Delta L}$. Since α changes with the wavelength, different interrogating wavelengths will lead to different $T(L)$. Taking into account the directivity of the circulator R_{DIR} and the reflection from the isolator R_{ISO}, the total backscattered/reflected power of the reference undisturbed system can be expressed as:

$$P_{B01} = \mathrm{P}_{01} \cdot \left[\mathrm{R}_{\mathrm{DIR}} + \mathrm{R}_{\mathrm{ray1}}(\mathrm{L}) + \mathrm{T}_1{}^2(\mathrm{L}) \cdot \mathrm{R}_{\mathrm{ISO}}\right]$$
$$P_{B02} = \mathrm{P}_{02} \cdot \left[\mathrm{R}_{\mathrm{DIR}} + \mathrm{R}_{\mathrm{ray2}}(\mathrm{L}) + \mathrm{T}_2{}^2(\mathrm{L}) \cdot \mathrm{R}_{\mathrm{ISO}}\right] \quad (2)$$

in which $R_{ray1(2)}(L)$ is the Rayleigh backscattered power coefficient that can be expressed as: $R_{ray}(\Delta L) = S\left(\frac{\alpha_s}{2\alpha}\right)(1 - e^{-2\alpha\Delta L})$[5]. α_s is the scattering coefficient of the Rayleigh scattering and is proportional to $1/\lambda^4$ [5], ΔL is the length of the fiber segment and S is a capture coefficient [5], which changes with the wavelength.

Let us consider that a reflective event with a return loss RL and insertion loss IL is introduced into the fiber at a distance of l ($l \le L$), and here we suppose RL is not changed with wavelength (referring non-reflective event, RL is usually higher than 75dB, e.g. bending). The transmitted power P_{T1} and the reflected power P_{B1} with interrogating wavelength λ_1 can be expressed as:

$$P_{T1} = P_{T01} \cdot 10^{\left(-\frac{IL_1}{10}\right)} \quad (3)$$
$$P_{B1} = P_0 \cdot \left[R_{DIR} + R_{ray1}(l) + \mathrm{T}_1{}^2(l) \cdot RL + [R_{ray1}(L) - R_{ray1}(l)] \cdot t_{n1}^2 + \mathrm{T}_1{}^2(L) \cdot t_{n1}^2 \cdot R_{ISO}\right] \quad (4)$$

With the second interrogating wavelength λ_2, P_{T2} and P_{B2} can be expressed as:

$$P_{T2} = P_{T02} \cdot 10^{\left(-\frac{IL_2}{10}\right)} \quad (5)$$
$$P_{B2} = P_0 \cdot \left[R_{DIR} + R_{ray2}(l) + \mathrm{T}_2{}^2(l) \cdot RL + [R_{ray2}(L) - R_{ray2}(l)] \cdot t_{n2}^2 + \mathrm{T}_2{}^2(L) \cdot t_{n2}^2 \cdot R_{ISO}\right] \quad (6)$$

With equation (1), (2) and (3), the normalized power reflection coefficient R_{n1} and R_{n2} can be written as:

$$R_{n1} = \frac{P_{B1}}{P_{B0}} = \frac{R_{DIR} + R_{ray1}(l) + \mathrm{T}_1{}^2(l) \cdot RL + [R_{ray1}(L) - R_{ray1}(l)] \cdot t_{n1}^2 + \mathrm{T}_1{}^2(L) \cdot t_{n1}^2 \cdot R_{ISO}}{\mathrm{R}_{\mathrm{DIR}} + \mathrm{R}_{\mathrm{ray1}}(\mathrm{L}) + \mathrm{T}_1{}^2(\mathrm{L}) \cdot \mathrm{R}_{\mathrm{ISO}}} \quad (7)$$

$$R_{n2} = \frac{P_{B2}}{P_{B0}} = \frac{R_{DIR}+R_{ray2}(l)+\mathrm{T_2}^2(l)\cdot RL+[R_{ray2}(L)-R_{ray2}(l)]\cdot t_{n2}^2+\mathrm{T_2}^2(L)\cdot t_{n2}^2\cdot R_{ISO}}{\mathrm{R_{DIR}+R_{ray2}(L)+T_2{}^2(L)\cdot R_{ISO}}} \quad (8)$$

where $t_{n1(2)}$ is the normalized power transmission coefficient, $P_{T1(2)}/P_{T01(2)}$, which is only dependent on the insertion loss of the event.

Since $R_{DIR}, \alpha, \alpha_s, R_{ISO}, and\ L$ are known parameters, and P_{B1}, P_{B2} and P_{T1}, P_{T2} can be obtained by the measurements, the problem finally becomes solving a set of two equations with only two unknown variables (i.e., l and RL).

Localization Accuracy of the 2λ-TRA Technique

In this section, analytical studies about the measurement accuracy of the proposed solution with different wavelength combinations are carried on. We take four commonly used wavelengths in our study, and made six different wavelength combinations. Parameters related to the calculation model are listed in Table 1[5].

Table 1: Parameters of four interrogating wavelengths

Interrogating wavelength λ (nm)	capture coefficient S	attenuation coefficient α (dB/km)	scattering coefficient αs (dB/km)
λ_1: 850	0.0013	2	1.9157
λ_2: 1310	0.001	0.35	0.33
λ_3: 1550	0.0012	0.2	0.1723
λ_4: 1650	0.0012	0.23	0.135

The powermeter output uncertainty mainly affects the localization accuracy of the proposed 2λ-TRA technique. Consequently, we introduce two measurement uncertainty coefficients ζ_1 and ζ_2, which are maximum measurement errors of the two powermeters, respectively. According to our previous experiments, both ζ_1 and ζ_2 are equal to 0.001 (0.1 %, repeatability test). The measurements can be therefore positioned inside the ranges $P_B \pm P_B\zeta_1$ and $P_T \pm P_T\zeta_2$ (here P_T and P_B are the exact power values). Simulations taking into account a uniform distribution of the measured powers within the above-mentioned ranges were undertaken (1000 samples). The length of the fiber (L) in our simulation is varied from 0 to 100 km to cover different applications (e.g. for sensing applications L is usually less than a few hundreds of meters, while referring to the field of telecommunication, such as the next generation PON system, a 100-km fiber length is normally employed). Here we consider a reflective event with a 20 dB return loss, and an event location l equal to L/4. We will discuss about the standard deviation below.

In Figure 2, the relationship between the localization error and the length of the fiber link with different wavelength combinations are presented. According to this figure, when the fiber length is less than 25km, three combinations (i.e. $\lambda_1+\lambda_2$, $\lambda_1+\lambda_3$ and $\lambda_1+\lambda_4$) give very good localization accuracies (less than 1m, while for OTDR measurement is usually around a few meters for a 10km-long fiber [1]). However, as the fiber length approaches over 35km, their localization errors show a rapid increase. Regarding the other three wavelength combinations (i.e. $\lambda_2+\lambda_3$, $\lambda_2+\lambda_4$ and $\lambda_3+\lambda_4$), the localization error remains almost constant (e.g. around 15m for $\lambda_2+\lambda_3$; more than 50 meters for OTDR measurement in a 100 km-long fiber [1]) as the fiber length increase, which could be an acceptable performance in long reach applications (i.e. the fiber length is longer than 20km). Figure 3 shows the relationship between the measured return loss error and the fiber length. Compared with Figure 3, the return loss error shows a similar trend. When the fiber length is less than 25 km, the return loss measurement error is around 0.0005dB for the three wavelength combinations $\lambda_1+\lambda_2$, $\lambda_1+\lambda_3$ and $\lambda_1+\lambda_4$. For the long reach cases, by using the wavelength combination of $\lambda_2+\lambda_3$, a 0.01 dB error can be reached. From the discussion above, one can expect that by choosing different interrogating wavelengths, high measurement accuracy can be achieved for both short range and long reach applications (i.e. for short range applications, one can use $\lambda_1+\lambda_2$ as the combination of interrogating wavelengths, while for the long reach cases, $\lambda_2+\lambda_3$ can be utilized).

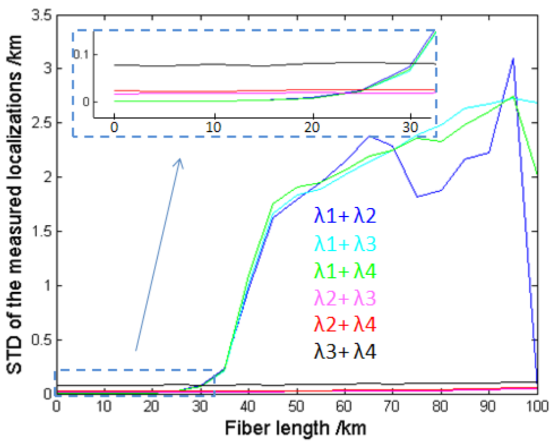

Figure 2: Analytical localization error with different interrogating wavelengths

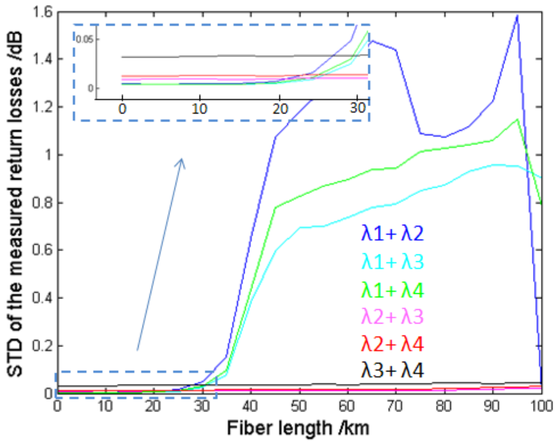

Figure 3: Analytical RL measurement error with different interrogating wavelengths

Conclusion

2λ-TRA scheme is proposed to localize and quantify a single reflective event on a fiber link. Analytical results show that by appropriately selecting two interrogating wavelengths, the proposed solution is able to detect the location and value of the return loss with sufficient measurement accuracy (i.e. 1m, 5×10^{-3} dB for a 20km-long fiber and 0.01dB, 15m for a 100-km long fiber). The whole system is characterized by a simple structure and low cost, the monitoring of both short range (less than 1km) and long range (100 km) systems can also be processed in a fast manner (a few seconds) thanks to its simple measurement of power variations. Consequently, the proposed 2λ-TRA solution provides a novel and simple solution for future distributed monitoring.

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