Accurate Fiber Length Measurements Using Time-Of-Flight Technique

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Abstract

Fiber artifacts of very well measured lengths are required for the calibration of optical time-domain reflectometers (OTDR). In this paper, accurate length measurement of different fiber lengths using the time-of-flight technique is performed. A setup is proposed to measure accurately lengths from 1 km to 40 km at 1550 nm and 1310 nm using a high speed electro-optic modulator, a photodetector and a time interval counter (TIC). This setup offers traceability to the SI unit of time, the second, (and hence to the meter by definition) by locking the time interval counter to the GPS-disciplined quartz oscillator. Additionally, the length of a recirculating loop artifact is measured and compared with the measurement made for the same fiber by the National physical laboratory of United Kingdom (NPL). Finally, a method is proposed to relatively correct the fiber refractive index to allow accurate fiber length measurement.

Keywords: Optical time domain reflectometer, fiber length measurement, OTDR calibration.

1. Introduction

Optical time domain reflectometers (OTDRs) are widely used in optical fiber network installation as a diagnostic tool. They are used to detect fault locations and measure loss along optical fiber links **(Danielson (1985))**. An OTDR determines the length of an optical fiber by measuring the time of flight of a modulated laser signal. In order to calibrate an OTDR, a more accurate system is required. Moreover, the measurement should be traceable to the SI unit of time, the second, and hence the SI unit of length, the meter, from definition of meter.

According to the European standard (EN 61746 (2005)), well-measured lengths of fiber artifacts can be used to calibrate the distance scale of an OTDR based on the concatenated or the recirculating loop methods **(European standard (2005))**.

Several techniques have been suggested to measure the length of an optical fiber. These methods are based on the frequency-shifted asymmetric Sagnac interferometer **(Bing et al. (2005))**, mode locking technique **(Hu et al. (2007))** and the time-of-flight technique **(European standard (2001))**. The first two methods are reported to have better accuracy than the third one; however, by the use of high speed optoelectronics, the third method can reach similar accuracies with ease of use and ability to measure the length of the recirculating loop fibers.

In this work, a setup is proposed which is based on the time-of-flight technique to measure accurately fiber lengths of 1 km to 40 km at 1550 nm and 1310 nm. A high speed electro-optic modulator, photodetector and a high resolution time interval counter will be used to utilize the

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accurate time-of-flight measurement. The measurement is traceable to the SI unit of time, the second, (and hence to the meter by definition) by locking the time interval counter to the GPS-disciplined quartz oscillator as well as by calibrating the time interval counter at the time and frequency laboratory. With a tiny modification in the used setup, it will be exploited to measure the length of a recirculating loop fiber. The recirculating loop measurement results will be compared to the results obtained from a previous measurement by the National physical laboratory of the United Kingdom (NPL). Finally, a method is proposed to relatively correct the fiber refractive index to allow accurate fiber length measurement.

Time-of-flight technique (TOF)

In order to measure the length of a long fiber of 1 km or more, TOF method can be easily implemented **(Bing et al. (2005))**. The time taken by a laser pulse to pass through the fiber is measured, and then the following equation is used to calculate the fiber length:

$$L_F = \frac{c_o \tau}{n} \qquad (1)$$

Where c_o= 299792458 m/s is the speed of light in vacuum, τ: is the time-of-flight, n: the group refractive index of the fiber.

Although this method is easy to implement, it requires fast rise-time pulse generator, fast photodetector and accurate time-interval-counter.

The length of the fiber can be greatly affected by its temperature. This effect can be obtained by partially differentiating equation (1), as follows:

$$\frac{\partial L_F}{\partial T} = \frac{\partial n}{\partial T}\frac{L_F}{n} \qquad (2)$$

where $\frac{\partial n}{\partial T}$, is the thermo-optic coefficient for silica fibers which is approximately 1×10^{-5} $^{o}C^{-1}$ **(Chang et al. (2000))**. For example, the change in the measured fiber length of 1 km for a change in temperature ∂T = 1 ^{o}C is around 7 mm when n ~ 1.46. The thermal expansion coefficient of optical fibers is two orders of magnitude lower than the thermo-optic coefficient, therefore, only the effect of temperature change on the refractive index is considered.

2. Materials and Methods

2.1. Fiber length measurement.

In this section the setup used to measure fiber length is discussed. Figure 1 shows the time-of-flight (TOF) determination setup. The system consists of two distributed feedback (DFB) lasers (EM4 wavelength=1556 nm, linewidth ≈ 3 MHz) and (Jiuzhou wavelength=1310 nm, linewidth = 0.2 nm), Electro-Optic intensity modulator (Lucent, model: X2623Y, Frequency ≈ 10 GHz (rise time <100 ps)), Oscilloscope (Yokogawa, DLM2022), pulse generator (SRS, DG645), digital delay generator (SRS, DG645), a photodetector (Lucent- 2860D-50, frequency: 10GHz) and time-interval counter (BNC-1105, interval counting accuracy: 50 ps). The TIC is locked to a GPS-disciplined quartz oscillator from Menlo systems.

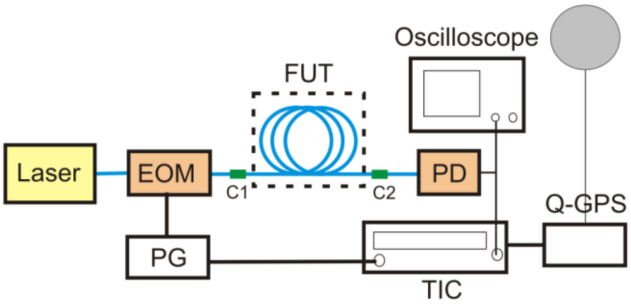

Figure 1: The system used to measure the fiber length, FUT: fiber under test, EOM: Electro-optic modulator, C1, C2: connectors, TIC: time-interval counter, PD: photodetector. PG: pulse generator, Q-GPS: GPS-disciplined quartz oscillator.

The pulse generator (PG) is used to send electrical pulses to the electro-optic modulator (EOM), which uses the pulses to modulate the laser light. The modulated laser pulses are sent through the fiber under test to a fast photodetector. The fast photodetector converts the fast laser pulses again to fast electrical pulses. The time delay between the pulses sent through the fiber and the reference pulses from the PG is measured using the time interval counter (TIC), and is designated by τ_{ins+F}. The FUT is then removed, points C1, C2 are connected and again the insertion delay of the setup is measured and is designated by τ_{ins}. The time delay in the fiber is calculated by subtracting the insertion delay from the total delay $\tau_F = \tau_{ins+F} - \tau_{ins}$. Afterwards, fiber length can be calculated from equation (1). The refractive index of the fiber is obtained from the manufacturer's datasheet at 1310 nm and 1550 nm to be 1.4677 and 1.4682, respectively. However, by comparing the length of a fiber measured with both wavelengths, a length-dependent-mismatch is noticed. The reason for this mismatch is attributed to the inaccurate refractive index provided by the manufacturer. Therefore, an equal correction is applied to both refractive indices of 1310 nm and of 1550 nm as depicted in Tables 1, 2, respectively. This correction is obtained from the slope of the error-length curve.

2.2. Recirculating loop length measurement.

A recirculating loop artifact (shown in Fig. 2.a) is used frequently to calibrate optical time domain reflectometers (OTDRs), since it offers easier determination of the distance scale deviation. It places a number of reflective features on the OTDR display, as shown in Figure 2.b. The first feature is the one obtained from the optical pulse travelling direct to the mirror through the lead-in fiber. The second feature is generated by the optical pulse travelling once through the loop, then to the mirror, and then back direct to the OTDR. The third pulse travels through the loop twice, etc. Therefore, the first pulse position indicates the length of the lead-in fiber, while the difference between the first and the second pulse indicates the loop length.

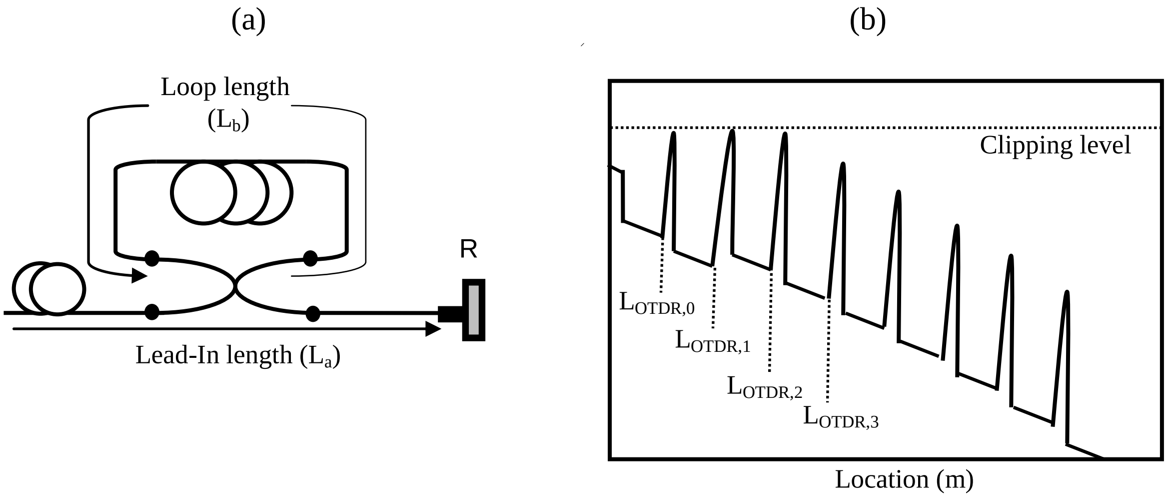

Figure 2: (a) the NPL recirculating delay-line, (b) OTDR trace produced by a recirculating delay-line.

The length of the lead-in fiber can be measured using the same method discussed in section 3.1; however, the loop fiber requires different technique to measure the time-of-flight of the consequent pulses. The setup is actually similar to the one given in Fig. 1; however, the output of the photodiode is connected with equal cable lengths to both channels of the TIC, as shown in Fig. 3. As a consequence, the TIC will give directly the time-of-flight of the pulses inside the loop only, without the need to measure the insertion delay of the setup separately.

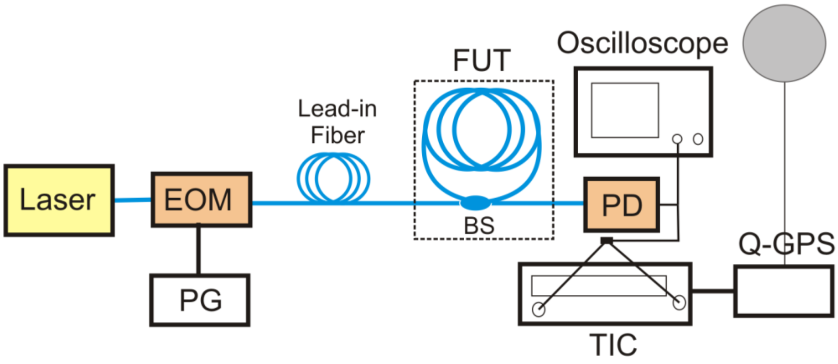

Figure 3: The setup used to measure loop length.

3. Results and Discussion

Fibers with lengths of 1 km, 10 km, 20 km, 30 km and 40 km as well as the recirculating delay line are measured at 1310 nm and at 1550 nm using the setup depicted in Fig. 1 and Fig. 3. The results are shown in Table 1 and Table 2, respectively. The measurement is performed at a laboratory temperature of 23 ^{o}C.

Table 1: Fiber lengths measurement results @ (1310 nm, 23 ^{o}C)

Nominal length	**TOF (τ)** Ins .+ Fiber (ns)	**TOF (τ)** Insertion (ns)	**TOF(τ)** Fiber (ns)	**Refractive Index (n)**	**Fiber length** @ 1310 nm (m)	**STD (m)**	**Uncertainty (m)**
1 km	5287.36	301.24	4986.12	1.46762	1018.52	0.04	± 0.08
10 km	49434.14	301.24	49132.9	1.46762	10036.44	0.04	± 0.08
20 km	98360.14	301.24	98058.9	1.46762	20030.62	0.04	± 0.09
30 km	147493.09	301.24	147191.85	1.46762	30067.07	0.04	± 0.09
40 km	196195.5	301.24	195894.26	1.46762	40015.58	0.04	± 0.10
2 km (lead-in)	11133.17	306.29	10826.88	1.46765	2211.57	0.04	± 0.08
13 km (loop)	67619.22	0	67619.22	1.46765	13812.38	0.14	± 0.28

Table 2: Fiber lengths measurement results @ (1550 nm , 23 ^{o}C)

Nominal length	**TOF (τ)** Ins .+ Fiber (ns)	**TOF (τ)** Insertion (ns)	**TOF(τ)** Fiber (ns)	**Refractive Index (n)**	**Fiber length** @ 1310 nm (m)	**STD (m)**	**Uncertainty (m)**
1 km	5231.94	243.95	4987.99	1.46828	1018.44	0.04	± 0.08
10 km	49399.36	243.95	49155.41	1.46828	10036.52	0.04	± 0.08
20 km	98347.5	243.95	98103.55	1.46828	20030.72	0.04	± 0.09
30 km	147503.16	243.95	147259.21	1.46828	30067.29	0.04	± 0.09
40 km	196225.73	243.95	195981.78	1.46828	40015.43	0.04	± 0.10
2 km (lead-in)	11080.65	249.1	10831.55	1.46825	2211.62	0.04	± 0.08
13 km (loop)	67647.08	0	67647.08	1.46825	13812.42	0.14	± 0.28

3.1 Comparison with NPL measured values for the recirculating loop

A comparison is made between the results obtained from NPL and NIS for the recirculating loop artefact at 1310 nm and 1550 nm. The measurements at both institutes are performed at 23 ^{o}C. The comparison results are shown in Figures 4 and 5. Good agreement is found between the comparative length measurement results for both of the lead-in and loop fibers from both institutes which show more or less similar uncertainties.

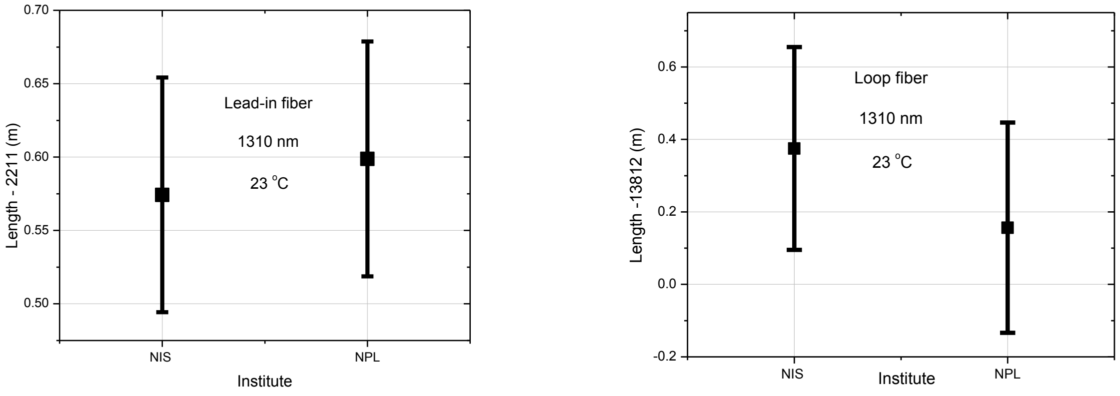

Figure 4: comparison between NIS and NPL results at 1310 nm for (a) lead-in (b) loop fibers.

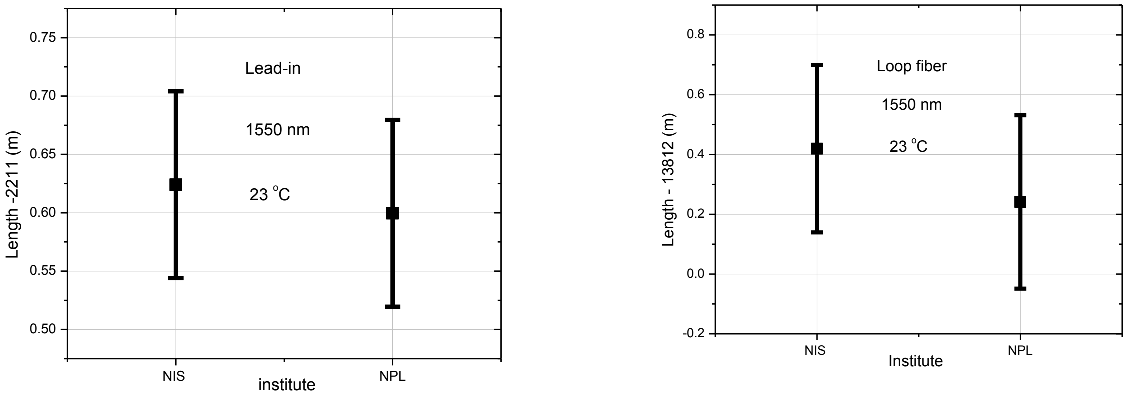

Figure 5: comparison between NIS and NPL results at 1550 nm for (a) lead-in (b) loop fibers.

3.2 Uncertainty analysis

In order to report the calibration result, uncertainties in the fiber length should be obtained. The guide to the expression of the uncertainty in measurement (GUM) is used to calculate the uncertainties **(BIPM (1995))**. The uncertainty in the measured length originates mainly from two contributors, namely, the refractive index and the time delay measurement. The uncertainty in the delay time measurements includes mainly the uncertainty in the time interval counter and the measurement statistical contribution. The uncertainty in the refractive index includes only the temperature dependence, since the manufacturer doesn’t state uncertainty for the refractive index determination. The contributors to the uncertainty are summarized in Table 3:

Table 3: The systematic contribution to the uncertainty for L_F.

Source of uncertainty	**Value (±)**	**Probability distribution**	**Divisor**	**Uncertainty (±)**	**Sensitivity Coefficient**	**Standard uncertainty**
Time interval counter	0.1 ns	Rectangular	$\sqrt{3}$	0.06 ns	2.05×10^{8}	± 1.2 cm
Temperature	0.2 °C	Rectangular	$\sqrt{3}$	0.1 °C	6.9×10^{-6} L	$\pm 6.9\times10^{-7}$ L (m)

The systematic contribution to the uncertainty for a fiber of length (L_F) is obtained from Table 3. The combined uncertainty can be calculated by adding in quadrature the systematic contribution in Table 3 to the statistical contribution (STD) in Tables 1, 2 for each length of fiber. The expanded uncertainties at confidence level of 95% are found by multiplying these values by 2. The final uncertainties for each fiber are shown in Tables 1, 2.

4. Conclusion

Accurate length measurement of different fiber lengths using the time-of-flight technique is performed. A setup is proposed and used to measure accurately lengths from 1 km to 40 km at 1550 nm and 1310 nm using high speed electro-optic modulator, photodetector and accurate time interval counter. The measurement is made traceable the SI unit of time, the second, by locking the time interval counter to the GPS-disciplined quartz oscillator and through calibration at the Time and Frequency laboratory. The length of a recirculating loop artifact is measured and compared to the measurement made for the same fiber by the NPL. Finally, a method is applied to relatively correct the fiber refractive index to allow accurate fiber length measurement.

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5.References

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الملخص باللغة العربية

قياس أطوال الألياف البصرية باستخدام تقنية قياس زمن مرور الضوء خلاله

أسامة محمد السيد تره ، حاتم حسين إبراهيم

المعهد القومي للقياس و المعايرة – الجيزة- ج.م.ع

إن كابلات الألياف البصرية القياسية ذات الأطوال المعنية بدقة كبيرة لا بديل عنها فى معايرة أجهزة المقياس الزمنى للضوءالمنعكس . هذا البحث يشتمل على قياسات أطوال ألياف بصرية بدقة عالية باستخدام تقنية قياس زمن مرور الضوء وقد تم بناء نظام ضوئى ـ إلكترونى لقياس الألياف البصرية ذوات الأطوال من 1 إلى 40 كيلو متر عند الأطوال الموجية 1310 و 1550 نانومتر باستخدام محور كهروضوئى و كاشف سريع .

هذا النظام يقدم وسيلة إسناد مرجعية إلى وحدة الزمن الخاصة بالنظام الدولى للقياس وهى (الثانية) وبالتالى إلى المتر وذلك بتثبيت عداد الفترة الزمنية على مذبذب القياس الكوارتز مع جهاز تحديد المواقع .

بالإضافة إلى أن كابل الألياف البصرية القياسى قد تمت مقارنة طوله مع القياسات التى تمت بمعهد المعايرة البريطانى وتم تعديل معامل إنكسار الألياف البصرية للسماح بقياسات أكثر دقة .