Length Measurement for Optical Transmission Line Using Interferometry

Takeshi Tsujimura[1], Koichi Yoshida[2] and Kuniaki Tanaka[3]
[1]*Department of Mechanical Engineering, Saga University*
[2]*Department of Information and Systems Engineering, Fukuoka Institute of Technology*
[3]*NTT corporation*
Japan

1. Introduction

More than half a million kilometres of aerial/underground optical telecommunication cable have been installed in Japan. A guaranteed telecommunication service is replacing the best-effort service as real-time streaming delivery increases. Fiber-to-the-home (FTTH) systems are mainly designed by passive optical network (PON) topology (ITU-T Recommendation G.983.1, 1998; Hornung et al., 1990; Sankawa et al., 2006). They are not allowed for even an instantaneous interruption day and night, because numerous customers suffer damage from it as 1 x 10^9 bits of data will be lost every second.

Telecommunication cables are required to be relocated in road construction and work on the water supply. Each optical fiber leading from an optical line terminal (OLT) in a telephone office to a customer's optical network unit (ONU) must be cut and reconnected as shown in Fig. 1. Customers expect real-time transmission for high-quality communications to continue uninterrupted, especially for video transmission services.

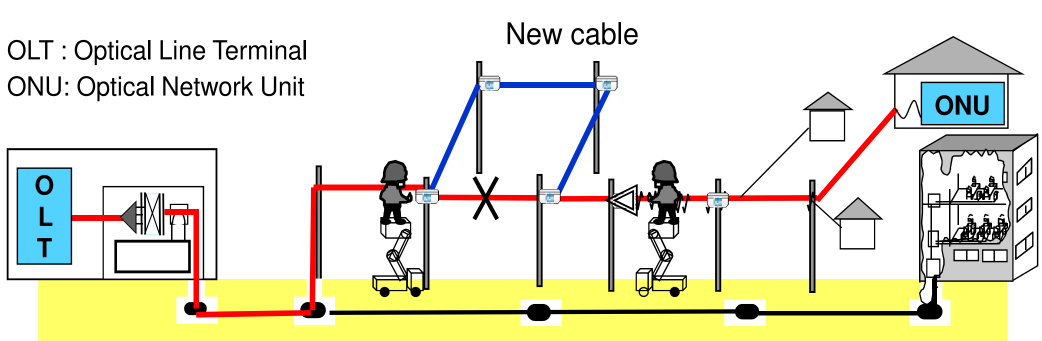


Fig. 1. Optical fiber cable replacement.

Several studies have reported on protection of PON system (Xu & Ho, 2001; Tanaka & Horiuchi, 2008). Electrical transmission apparatus can maintain communication without interruption, even when optical cables are temporarily cut. The system is complicated and any transmission delay during O/E conversion is fatal to real-time communication. Although it is desirable to directly switch the transmission medium itself, it had been thought that some data bits would inevitably be lost during the replacement of optical fibers. An optical fiber cable transfer splicing system has been developed to minimize cable replacing time (Watanabe et al., 1992; Tanaka et al., 2002). It disconnects an optical fiber and exchanges it for another in a flash. It takes 30 ms to switch a transmission line, and more than 2 seconds to restore communications with, for example, a gigabit Ethernet passive optical network (GE-PON) (Azuma et al., 2008). Neither the PON protection technique nor the splicing system avoids communication failures because they cannot reduce the disconnecting time absolutely to zero.

The authors have developed an interruption-free replacement method for in-service telecommunication lines, which can be applied to the current PON system equipped with conventional OLTs and ONUs (Tsujimura et al., 2010; Tanaka et al., 2009; Yoshida & Tsujimura, 2010). Two essential techniques were newly proposed; a measurement method and an adjustment system for the transmission line length. The latter continuously lengthens/shortens the transmission line over very long distances without losing transmitted data based on free space optics (FSO) system (Tsujimura et al., 2009b; Yoshida et al., 2009). The former distinguishes the difference between the duplicated line lengths using interferometry (Tsujimura et al., 2009a). Interferometry is the technique of diagnosing the properties of two or more lasers or waves by studying the pattern of interference created by their superposition. It is an important investigative technique in the fields of astronomy, fiber optics, optical metrology and so on. Studies on optical interferometry are reported to improve tiny optical devices (Saunders & Hardcastle, 1994; Cao & Cartledge, 2002; Torregrosa et al., 2007). We have applied the optical interferometry technique to measure length of several kilometers of transmission lines with a 10 mm resolution in this study.

This paper reveals the problems in replacing optical cables first. It proposes a switching method of optical fiber transmission lines next. We design a shunt system for in-service optical fibers. Then an optical line length measurement method is studied to distinguish the difference of two lines by evaluating interfered optical pulses. An optical line switching system is designed, and a line length adjustment system is prototyped. The proposed system is applied to a 15 km GE-PON optical fiber network while adding a 10 m extension to show the efficiency of this approach when replacing in-service optical cables. Finally, we discuss some proposal for improvement of line length measurement.

2. Optical cable replacement

First of all, fundamental investigations were conducted on the effects of transmission interruption on the telecommunication service.

When an optical fiber line was intensionally disconnected in a short time, transmission broke off and was restored by PON transmission system. Figure 2 and 3 show the experimental results of transmission characteristics when GE-PON optical communication line is switched using high-speed line transfer. Figure 2 expresses the relationship between interruption time and optical network unit (ONU) restoration time for 4 ONUs. Even if an optical fiber line was reconnected only in 100 ns, the transmission system took about 6 seconds to restore the telecommunication service. Up to 8 ONUs can be connected to an OLT. It took more than 10 seconds if eight ONUs were connected to an OLT as shown in Fig. 3, which indicates that the restoration time increases in relation to the number of ONUs.

These results suggest that communication service is inevitably interrupted no matter how quick the conventional method reconnects the transmission line. That is why a new switching method is necessary to maintain communications completely during optical cable replacement and thus provide a highly reliable network.

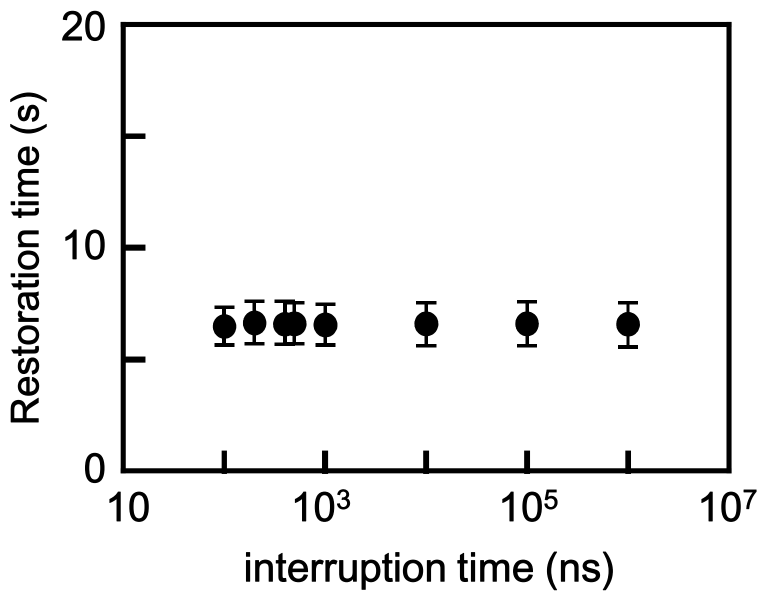


Fig. 2. Relationship between interruption time and restoration time.

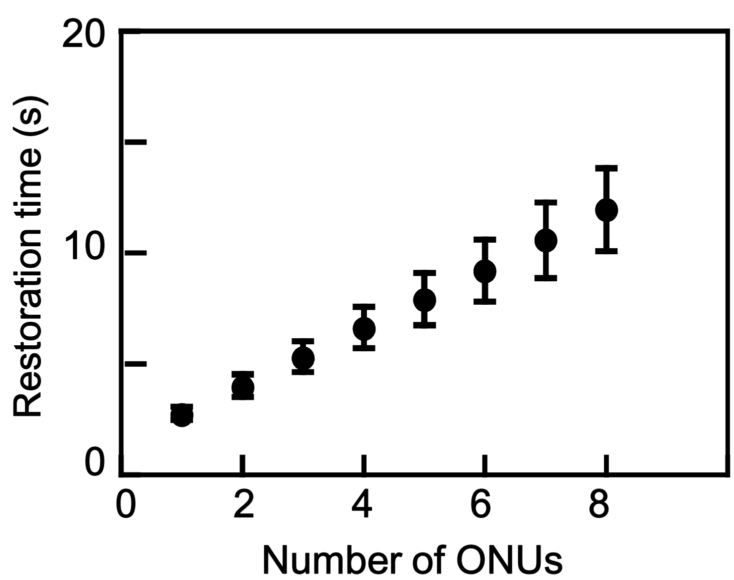


Fig. 3. Relationship between number of ONUs and restoration time.

3. Optical fiber line switching

3.1 Optical line switching technique

We propose an optical line switching technique that uses duplex transmission lines as shown in Fig. 4. Normal transmission system consists of an OLT, ONUs, and an optical fiber labeled 'regular line' in Fig. 4. Signals are bidirectionally transmitted along the line through a wavelength independent optical coupler (WIC) and an optical splitter. Our proposed technique requires a detour optical fiber to temporarily transmit signals. It also uses a test light whose wavelength is different from ones for signal transmission. The test light is created by an optical frequency-chirped pulse light source, and reaches an oscilloscope through the optical splitter, the regular/detour line, and the WIC. An optical line length measuring method detects the optical path difference between the detour and the regular line with these arrangements. An optical line length adjusting method controls the detour line length in virtue of FSO device.

Because either of two lines are managed to keep connection and to transmit signals at any time, the entire transmission system are secured against interruption. One of optical cables can be freely cut or reconnected, while the other cable maintains connected and transmits signals.

In order to avoid suspending transmission, the communication conditions have to be kept in the physical layer, for example, carrier power or signal phase. Thus, the following two conditions must be met while exchanging an in-service line for a spare line,

a. No transmission signals must be lost,
b. Transmission time in a protocol must be maintained.

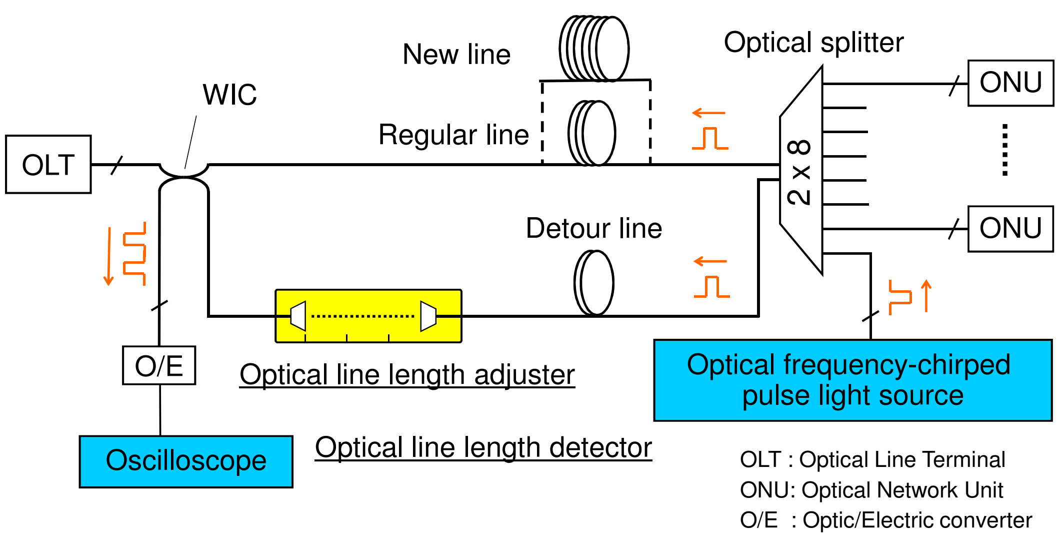


Fig. 4. Duplex optical fiber transmission system.

The conditions are satisfied by equalizing the transmission times of both signals transmitted through the duplicated lines. We accomplish this by tuning the length of the detour line.

The optical line replacement procedure, illustrated in Fig. 5 where the transmission lines are simplified, is as follows:

Step 0. Signals are ordinarily transmitted through an optical fiber (regular line) between an OLT and ONUs through a 2x8 optical splitter.

Step 1. A detour line is established between the WIC and the 2x8 optical splitter. A transmission system in the telephone office commonly equips with a WIC next to an OLT. A 1650 nm LD is connected to one of the branches of the 2x8 optical splitter.

Step 2. The detour line length is measured with a 1650 nm test light using an optical line length measuring method, and is adjusted to the same length as the regular line using an optical line length adjusting method.

Step 3. Once the lengths of the two lines coincide, the transmission signals are also launched into the detour line.

Step 4. The regular line is cut. Transmission keeps connected because the signals travels through the detour line. A long-wavelength pass filter (LWPF) is temporarily installed in the new line.

Step 5. The LWPF passes the test light alone through the new line.

Step 6. The test light measures the lengths of the new line and the detour line. The detour line is adjusted to the new line while communications are maintained. The LWPF keeps preventing the optical pulses for telecommunication from traveling through the new line.

Step 7. The LWPF is then removed and the transmission is duplicated. The detour line is finally cut off.

Step 8. Replacement of the optical fiber line is completed without any interruption.

Step 0: Signals travel through regular line.

Step 1: Set detour line.

Step 2: Adjust detour line to regular line.

Step 3: Multiplex optical signals.

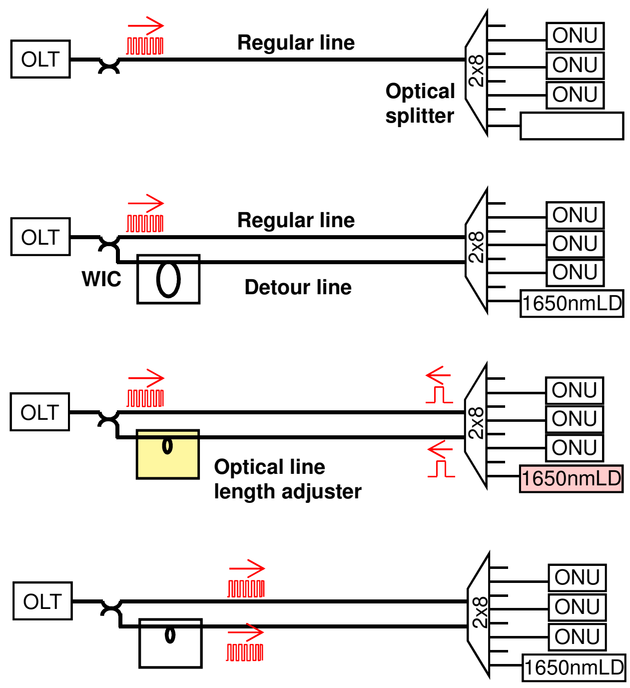


Fig. 5. Part I

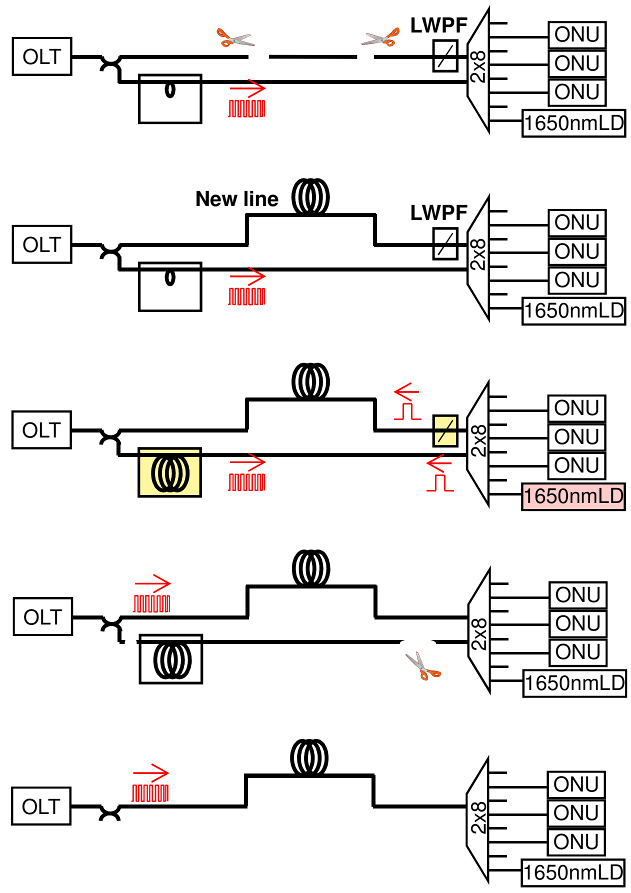
Step 4: Cut regular line.

Step 5: Connect new line.

Step 6: Adjust detour line to new line.

Step 7: Cut off detour line.

Step 8: Complete replacement.



Part II

Fig. 5. Optical line replacement procedure.

3.2 Optical line shunt system

The authors have designed an optical line shunt system, and a switching procedure for three wavelengths, namely 1310 and 1490 nm for GE-PON transmission, and 1650 nm for measurement. The optical line shunt system is installed in a telephone office. It is composed of an optical line length detector and an optical line length adjuster. Figure 6 shows an individual optical fiber line in a GE-PON transmission system. Optical pulse signals at two wavelengths are bidirectionally transmitted through a regular line between customers' ONUs and an OLT in a telephone office via a wavelength independent optical coupler (WIC) and a 2x8 optical splitter (2x8 SP), respectively.

A test light at a wavelength different from those of the transmission signals is sent from one of the optical splitter's ports to the duplicated lines. We use a 1650 distributed feedback laser diode (DFB-LD) whose pulse width is 200 ns as a test light source. An oscilloscope is connected to the optical coupler to detect the test light through a long-wavelength pass filter (LWPF). The optical line length adjuster is an FSO application (Yoshida et al., 2011; Willebrand et al., 1999). Some optical switches (SW) and optical fiber selectors (FS) control the flow of the optical signals managed by a PC. The optical pulses are compensated by 1650 and 1310/1490 nm amplifiers (Fukada et al., 2008).

The proposed method temporarily provides a duplicate transmission line as shown in Fig. 6 to replace optical fiber lines. A detour line is prepared in advance through which to divert signals while the existing line (regular line) is replaced with a new one.

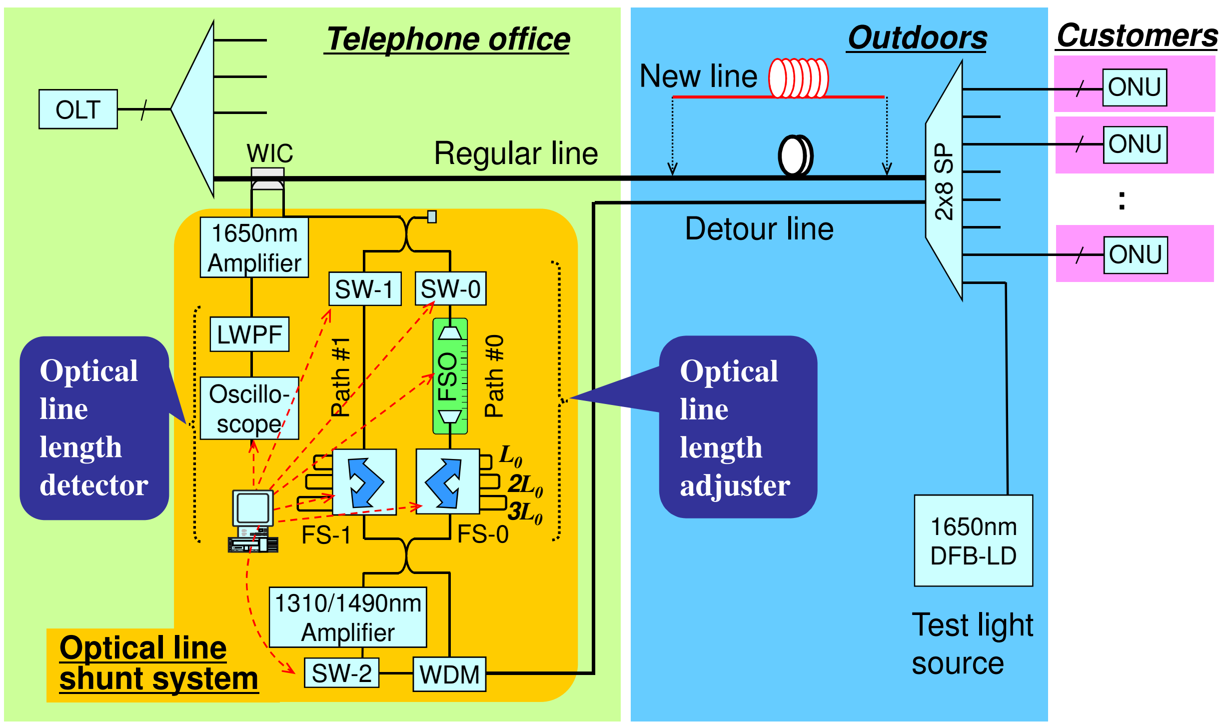


Fig. 6. Shunt system of optical fiber transmission line.

This system transfers signals between the two lines. Signals are duplicated at the moment of changeover to maintain continuous communications. The signals travel separately through the two lines to a receiver. A difference in the line lengths leads to a difference in the signals' arrival times. A communication fault occurs if, as a result of their proximity, the waveforms of the two arriving signals are too blurred for the signals to be identified as discrete. Thus it is important to adjust the lengths of both lines precisely.

We investigated the tolerance of the multiplexed signal synchronicity in advance. The transmission quality is observed by changing the difference between the duplicated line lengths. The results show that the transmission linkage is maintained if the difference is within 80 mm as with GE-PON. A multiplexed signal cannot be perceived as a single bit when the duplicated line lengths have a larger gap for 1 Gbit/s transmission. Because these characteristics depend on the periodic length of a transmission bit, the requirement is assumed to be more severe when the method is applied to higher-speed communication services.

Experiments determined that the tolerance of the difference in line length is 80 mm with regard to the GE-PON transmission system.

Accordingly, the proposed system controls the adjustment procedure so that the difference in length between the detour and regular lines is adjusted within 80 mm.

We next constructed a prototype of the optical line shunt system to apply to a GE-PON optical fiber line replacement according to the procedure described above.

An optical line length adjuster, shown in Fig. 7, was installed along the detour line. The adjuster was equipped with two retroreflectors, which directly faced each other as illustrated in Fig. 8. Optical pulses were transmitted through an optical fiber, divided into three wavelengths by wavelength division multiplexing (WDM) couplers, and discharged separately into the air from collimators. They traveled 10 times between the retroreflectors, and were introduced into the opposite optical fiber. The number of reflections was determined based on the retroreflector arrangement.

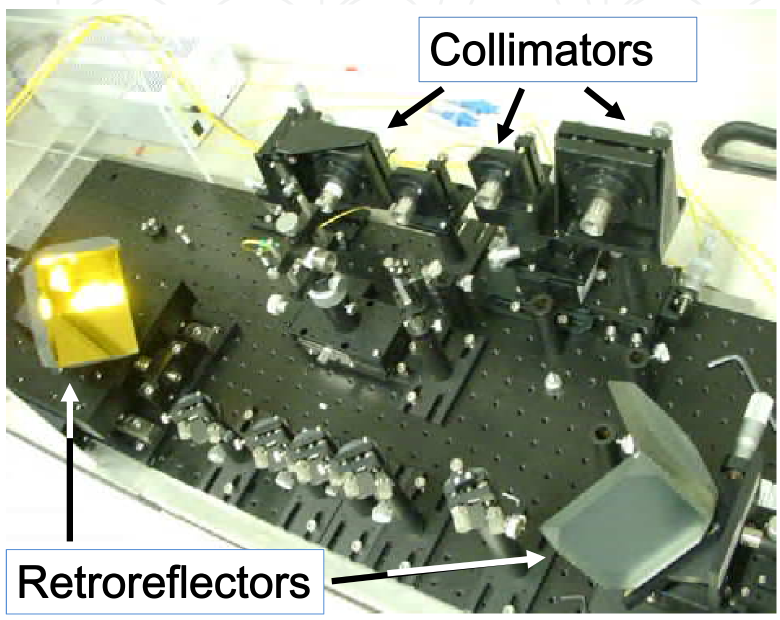


Fig. 7. Photos of optics line length adjuster.

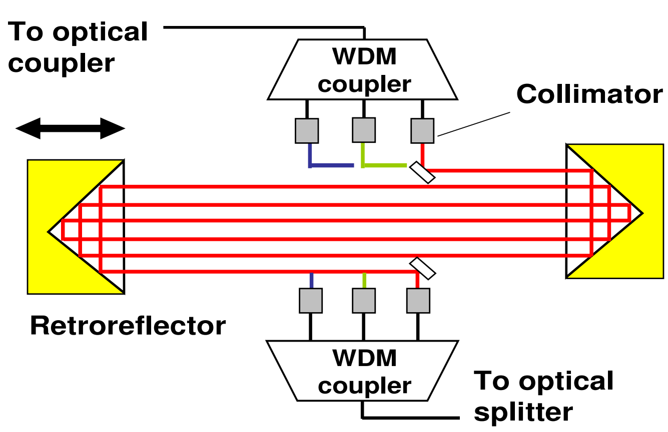


Fig. 8. Free-space optics line length adjuster.

The detour line between the retroreflectors consisted of an FSO system. The detour line length could be easily adjusted by controlling the retroreflector interval with a resolution of 0.14 mm with a motorized sliding stage. Optical pulses travel **n**-times faster in the air than in an optical fiber, where **n** is the refractive index of the optical fiber. Thus the optical line length adjuster lengthens/shortens the corresponding optical fiber length, ***L***

$$L = k\,W / n, \tag{1}$$

where $\boldsymbol{k}$, $\boldsymbol{W}$, $\boldsymbol{n}$ are the number of journeys between the retroreflectors, the retroreflector interval, and the refractive index of optical fiber, respectively.

The FSO lengthens the optical line length up to L_0.

$$L_0 = k\,(W_{max} - W_{min})/\,n, \tag{2}$$

where W_{max} and W_{min} are the maximum and minimum retroreflector intervals. The retroreflector stroke of our prototype, W_{max}- W_{min}, was 0.3 m, the refractive index, $\boldsymbol{n}$, of the optical fiber was 1.46, the number of journeys, $\boldsymbol{k}$ was 10, and the optical line span, L_0, tuned by the adjuster was 2 m. Our prototype adjusted the detour line length with a resolution of 0.1 mm.

The limit of the adjustable range is a practical problem when this system is applied to several kilometers of access network. Therefore, we designed an optical line length accumulator. The optical line length adjuster contains two optical paths, #0 and #1, as shown in Fig. 6. An optical switch (SW) and an optical fiber selector (FS) are installed in each path. Optical switches control the optical pulse flow. Each optical fiber selector is equipped with various lengths of optical fiber, for example L_0, $2L_0$ and $3L_0$. The path length can be discretely changed by choosing any one of them.

The optical line length adjuster can extend the detour line as much as required using the operation shown in Fig. 9. First, the FSO system lengthens path #0 by L_0 by gradually increasing the retroreflector interval. After the optical fiber selector, FS-1, has selected an optical fiber of length L_0, the active line is switched from path #0 to path #1 at time t_0. The FSO system then returns to the origin, and the optical fiber selector, FS-0, selects an optical fiber of length L_0 instead to keep the length of path #0 at L_0. The FSO system increases the retroreflector interval again at time $2t_0$ to repeat the same operation. In this way the adjuster accumulates spans extended by the FSO system. The scanning time of our prototype, t_0, was 10 seconds, because the retroreflector moved along the motorized sliding stage at 30 mm/s.

The optical line length adjuster enables us to lengthen/shorten the detour line while continuing to transmit optical signals.

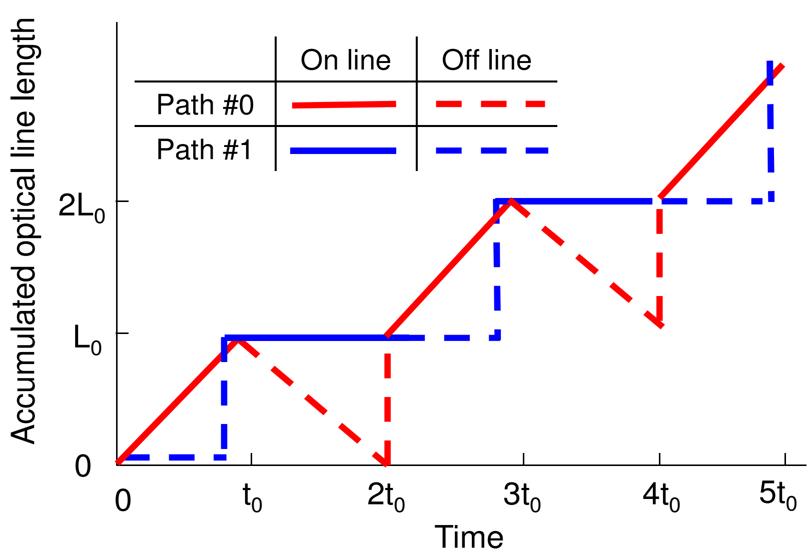


Fig. 9. Accumulation of optics line length.

4. Optical line length measurement

The proposed system uses laser pulses at a wavelength of 1650 mm to measure the optical path length. They are introduced from an optical splitter, duplicated, and transmitted toward the OLT through the active and detour lines.

They are distributed by an optical coupler just in front of the OLT, and observed with an oscilloscope. The conventional measurement method evaluates the arrival time interval between the duplicated signals, and converts it to the difference between the lengths of the regular line and the detour line at a resolution of 1 m.

The difference in line length, ΔL is described as

$$\Delta L = c \cdot \Delta t \ / \ n, \tag{3}$$

where c is the speed of light, Δt is the difference between the signal arrival times for the regular and detour lines, and n is the refractive index of optical fiber.

Figure 10 shows the received pulses observed with an oscilloscope. When the detour line was 100 m shorter than the regular line, pulses traveling through the detour reached the oscilloscope about 500 ns earlier than through the regular line as shown in Fig 10 (a). The proposed system lengthened the detour line using the optical path length adjuster. Consequently, the former pulse approached the latter. Figure 10 (b) is an example when the gap was shorten to 20 m, where the regular line pulse arrived after a delay of 100 ns. This method failed if the difference between the line lengths was less than 1 m, because the two pulses combined as shown in Fig. 10 (c).

That is why the authors have developed an advanced technique for measuring a difference of less than 1 m between optical line lengths. Interferometry enables us to obtain more detailed measurements even when the optical pulses combine. A chirped light source generates interference in the waveform of a unified pulse.

A 1650 nm laser pulse, discharged from the test light source, is devided by the 2x8 optical splitter. Two pulses travels through the detour and regular line separately toward the oscilloscope.

Both pulses along the regular line, $E\ (L_1, t)$, and the detour line, $E\ (L_2, t)$ are expressed as

$$E\ (L_1, t) = A_1 \exp\left[-i\ (k \cdot n \cdot L_1 - \omega_1 \cdot t + \phi_0)\ \right], \tag{4}$$

$$E\ (L_2, t) = A_2 \exp\left[-i\ (k \cdot n \cdot L_2 - \omega_2 \cdot t + \phi_0)\ \right], \tag{5}$$

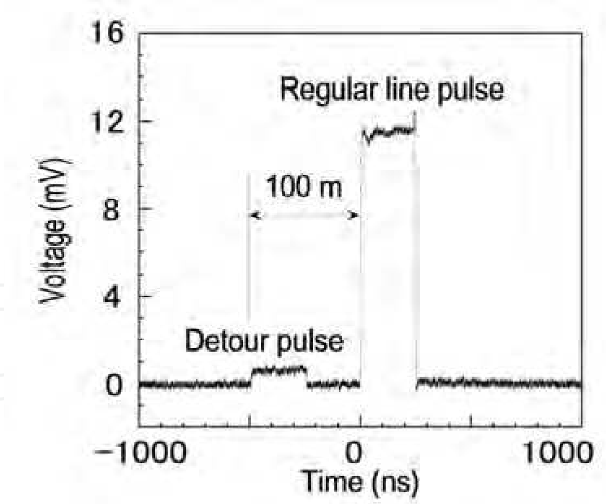
where A_j, k, n, L_j, ω_j, t, and ϕ_0 denote amplitude, wavenumber in a vacuum, refractive index of optical fiber, line length, frequency, time, and initial phase, respectively. Subscript j represents the regular line, 1, or the detour line, 2.

The intensity of a waveform with interference, I, is calculated by taking the square sum as

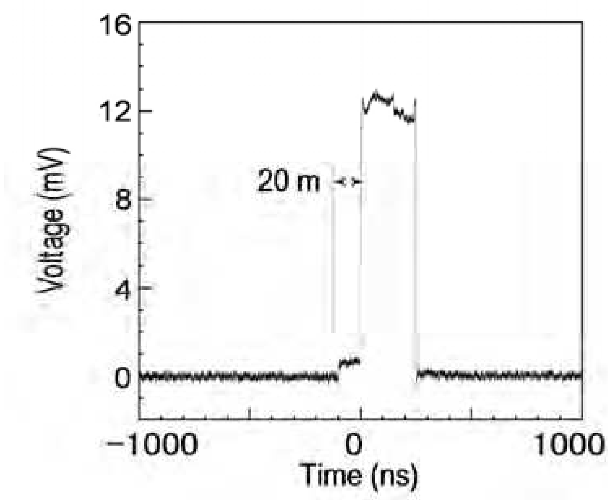
$$I = \left|\ E\ (L_1, t) + E\ (L_2, t)\ \right|^2$$

$$= A_1^2 + A_2^2 + 2\ A_1\ A_2 \cos\ (k \cdot n \cdot \Delta L - \Delta\omega \cdot t)\ , \tag{6}$$

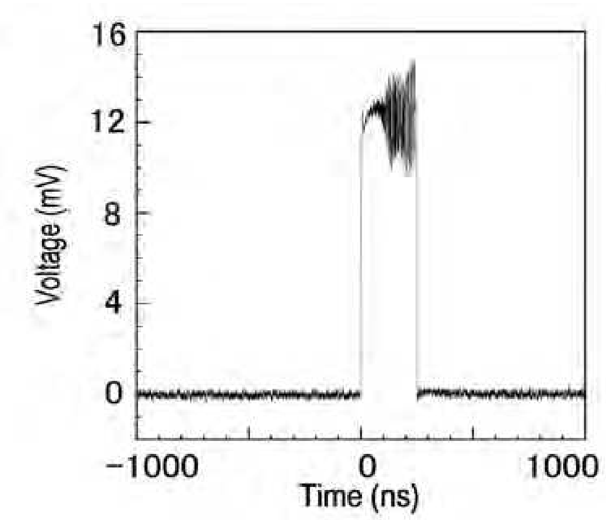
where ΔL and $\Delta\omega$ represent the differences between line lengths and frequencies, respectively.



(a) Optical path difference 100m.



(b) Optical path difference 20m.



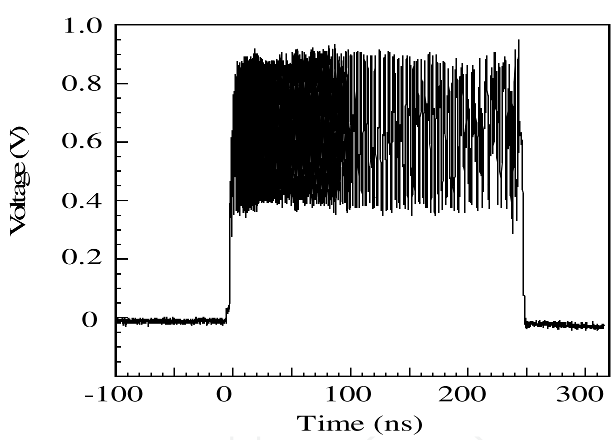
(c) Optical path difference 1m.

Fig. 10. Delay of duplicated received pulse.

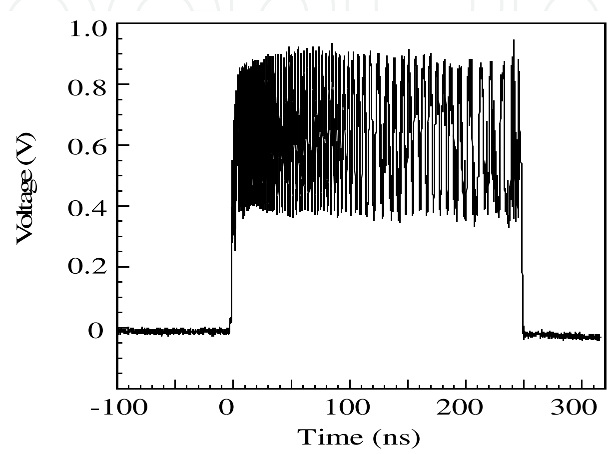
The waveform with interference depends on the delay between the pulses' arrival times. Experiments were carried out to obtain time-domain waveforms as shown in Fig. 11. When the optical path difference was 1 m, the waveform contained high-frequency waves as shown in Fig. 11 (a). The less the gap became, the lower-frequency the interfered waveform was composed of. Figures 11 (b) and (c) express that phenomenon. When the lengths of two lines coincided, a quite low-frequency waveform was observed as shown in Fig. 11 (d).

A Fourier-transform spectrum reveals the characteristics. When the optical path difference was 1 m, the waveform with interference was composed of the power spectrum shown in Fig. 12 (a). The peak power represented that the major frequency component was around 700 MHz. Figure 12 (b) and (c) indicate that the peak powers for gaps of 0.5 and 0.1 m were around 400 and 70 MHz, respectively. It became difficult to determine the peak for smaller gaps, because the frequency peak became so low that it was hidden by the near direct-current part of the frequency component. When the lengths of duplicated lines coincided, the power spectrum was obtained as Fig. 12 (d).

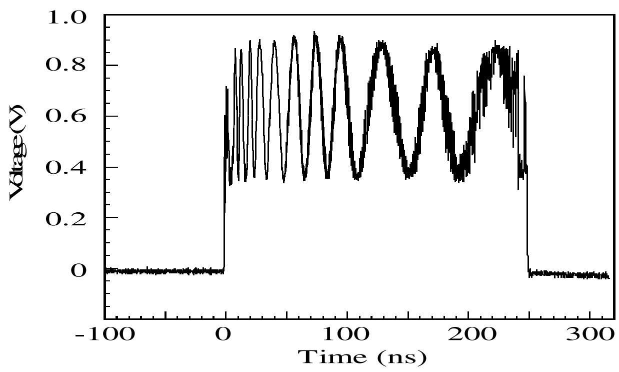
An evaluation of the frequency characteristics in the interfered waveforms showed that the peak power frequencies are proportional to the difference between the line lengths from -1 to 1 m as shown in Fig. 13, where the horizontal and vertical axes express the optical path difference and the frequency for the maximum power of Fourier-transformed spectrum, respectively. This result helps us to determine the optimal position for adjustment. The optimal position where the line lengths coincide can be estimated by extrapolating the data.



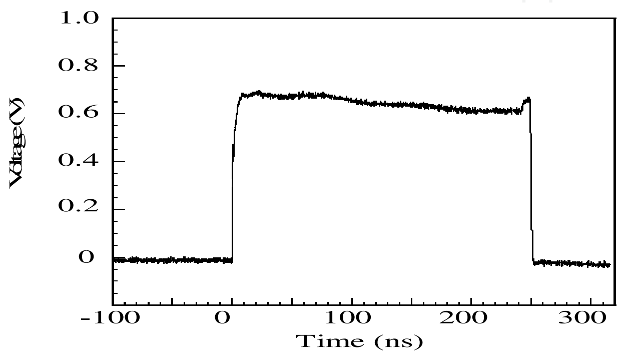
(a) Optical path difference 1 m.



(b) Optical path difference 0.5 m.

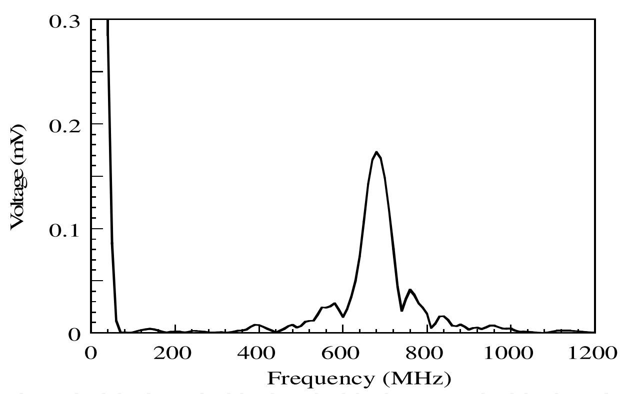


(c) Optical path difference 0.1 m.

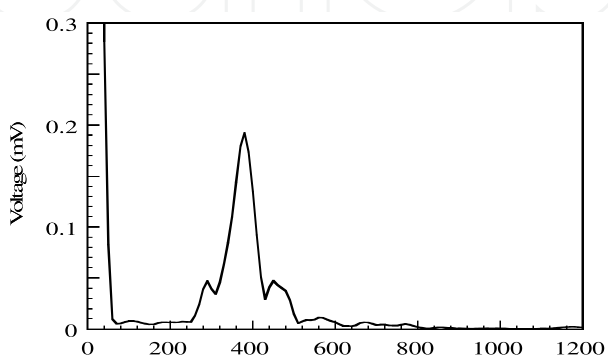


(d) Optical path difference 0 m.

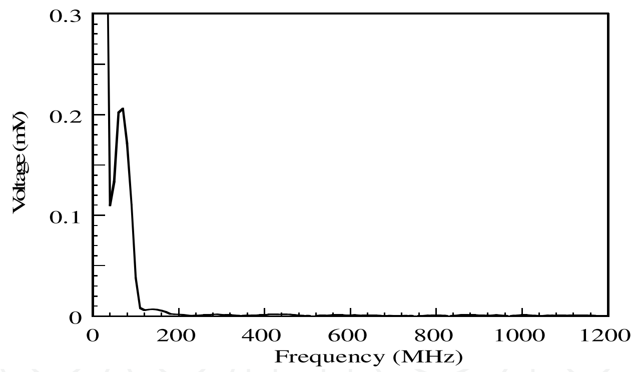
Fig. 11. Time-domain unified optical pulses.



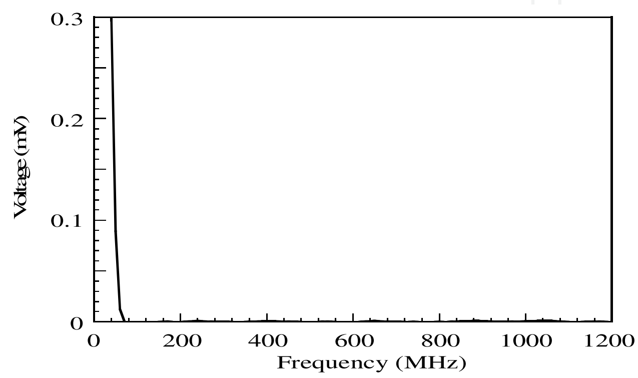
(a) Optical path difference 1 m.



(b) Optical path difference 0.5 m.



(c) Optical path difference 0.1 m.



(d) Optical path difference 0 m.

Fig. 12. Frequency-domain unified optical pulses.

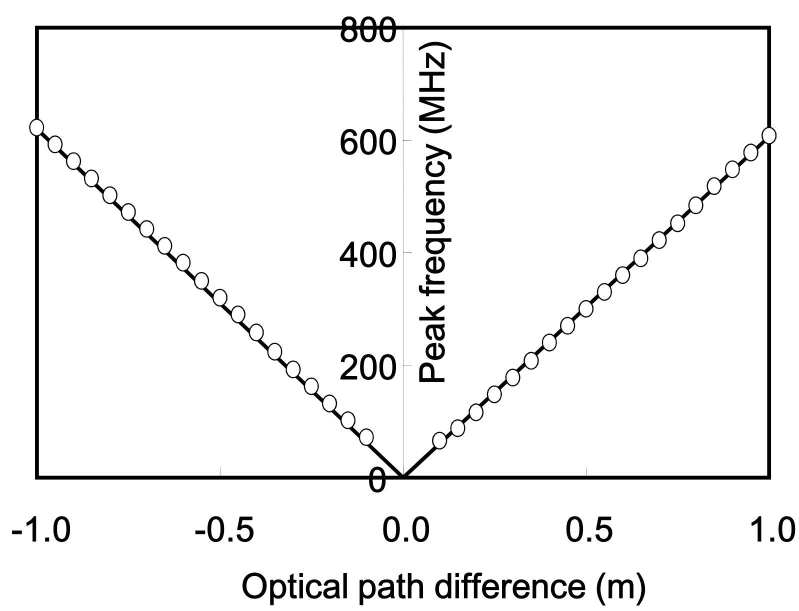


Fig. 13. Estimation of line length coincidence.

Our investigation has established a technique for distinguishing the difference between line lengths to an accuracy of better than 10 mm by analyzing interfering waveforms created by chirped laser pulses. We have realized a complete length measurement for optical transmission lines from 100 m to 10 mm.

We finally applied the prototype of the optical line shunt system to a 15 km GE-PON optical transmission line replacement. Photographs of our experimental setup are shown in Fig. 14. Figure 14 (a), (b), and (c) display a whole system for experimental optical transmission line, the side view, and the perspective view of the optical line length adjuster, respectively.

A 10 m optical fiber extension was added to the transmission line, while optical signals were switched between the duplicated lines during transmission. We have evaluated the frame loss that occurred during optical line replacement by measuring with a SmartBit network performance analyzer (Spilent Communications, 2011). Optical line length difference was purposely set at 0, 50, 80 and 120 mm in order to verify the effects of measurement accuracy. Same optical line replacement operation, illustrated in Fig. 5, was conducted for each case. No frame loss was observed at any stage of the replacement procedure if the difference between the duplicated line lengths was less than 80 mm. If the difference exceeded 80 mm, signal multiplexing caused frame loss at step 3 in Fig. 5.

We also evaluated communication quality of the transmission signals through duplicated lines. A 1488.6 nm optical pulse was actually transmitted along both detour and regular lines. Figure 15 shows the eye diagrams of the received signals with regard to optical path difference, ΔL, 1, 22, 44, 66, 88, and 110 mm. If two line lengths were close, communication quality was satisfactory as the eye opened wide in the diagram. When the difference became larger, the transmitted signals turned out erroneous because binary bit patterns were breaking.

As a result, we confirmed that the optical signals were completely switched between the regular, detour, and new lines on condition that the line length was adjusted with sufficient accuracy. The experimental results proved that our proposed system successfully relocated an in-service broadband network without any service interruption.

5. Improvement of line length measurement

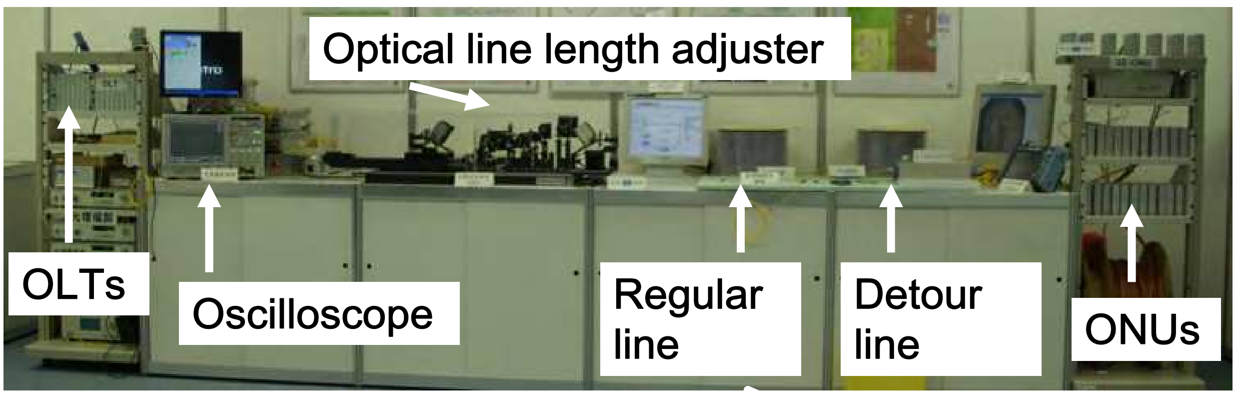
5.1 Sensitivity improvement due to narrow pulse width

We used a 1650 nm DFB-LD as a test light source. Because it was chirped nonlinearly, interference depended on the pulse width. Experiments were conducted to evaluate the effects on the power spectrum of the interfered waveform with regard to several pulse widths 20, 50, 100, 200, and 500 ns.

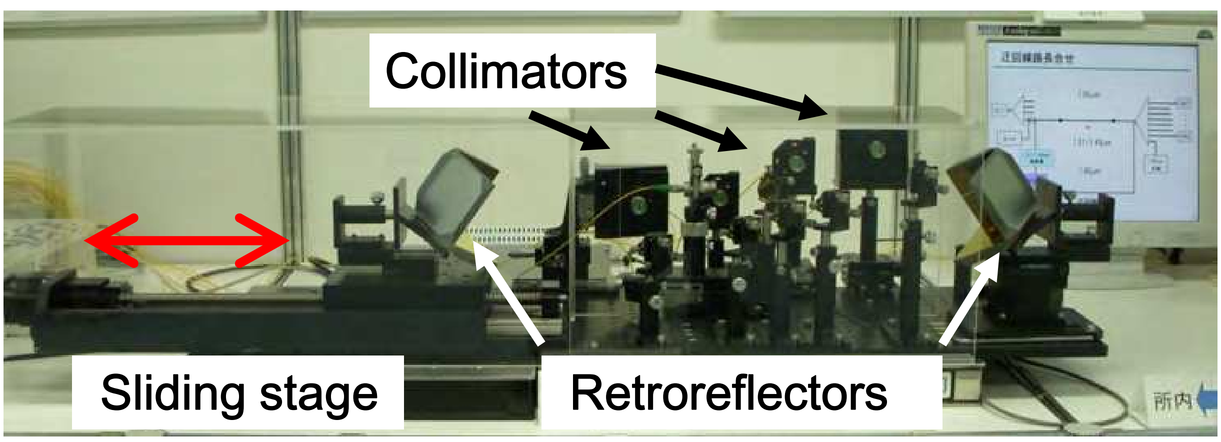
The results indicated that the test light pulse with narrower width provided higher sensitivity in estimating optical line length coincidence as shown in Fig. 16, where the horizontal and vertical axes express the optical path difference and the frequency for the maximum power of Fourier-transformed spectrum, respectively. Note that in the practical usage of the narrow width pulse with an oscilloscope, measurable range is restricted by the upper limit of the Fourier-transformed frequency. For example, a test light with 20 ns pulse width has a sensitivity of 6 MHz/mm while 1 GHz oscilloscope is necessary to identify an optical path difference of 150 mm.

5.2 Deterministic line length detection using frequency shift method

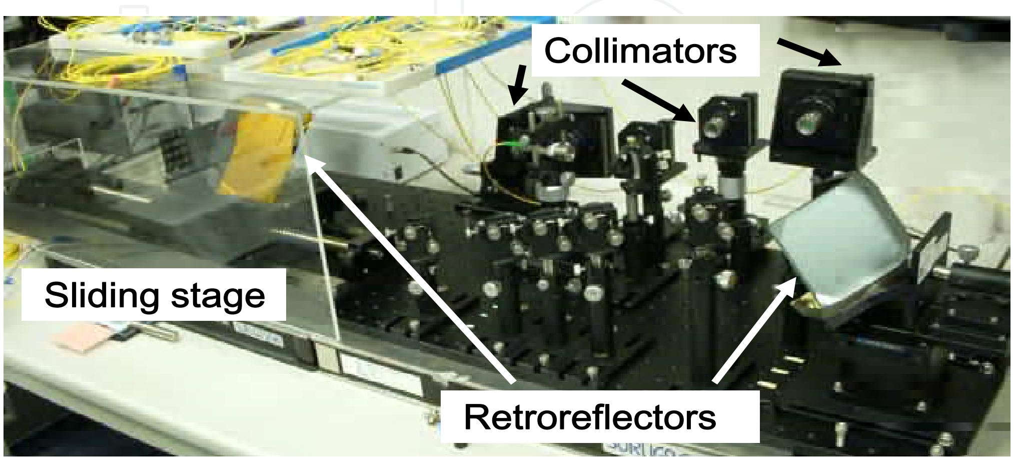
As discussed in Section 4, it is difficult for the above proposed method to directly identify the point where the lengths of the detour and regular lines coincide because the frequency peak is hidden by the near direct-current part of the frequency component in the power spectrum.



(a) Whole system for experimental optical transmission line.



(b) Side view of optical line length adjuster.



(c) Perspective view of optical line length adjuster.

Fig. 14. Photographs of optical line replacement experiments.

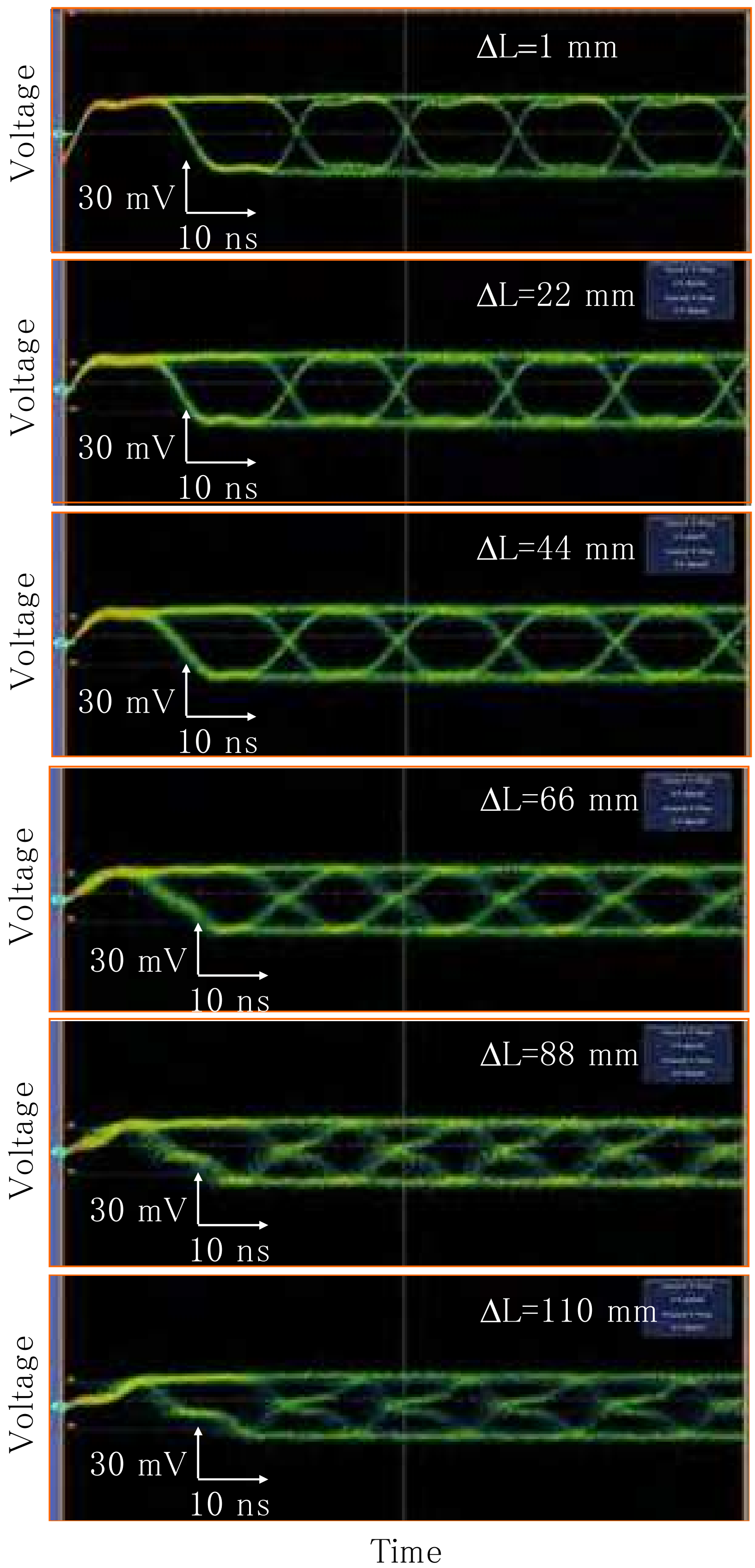


Fig. 15. Eyediagram of duplicated transmission signal.

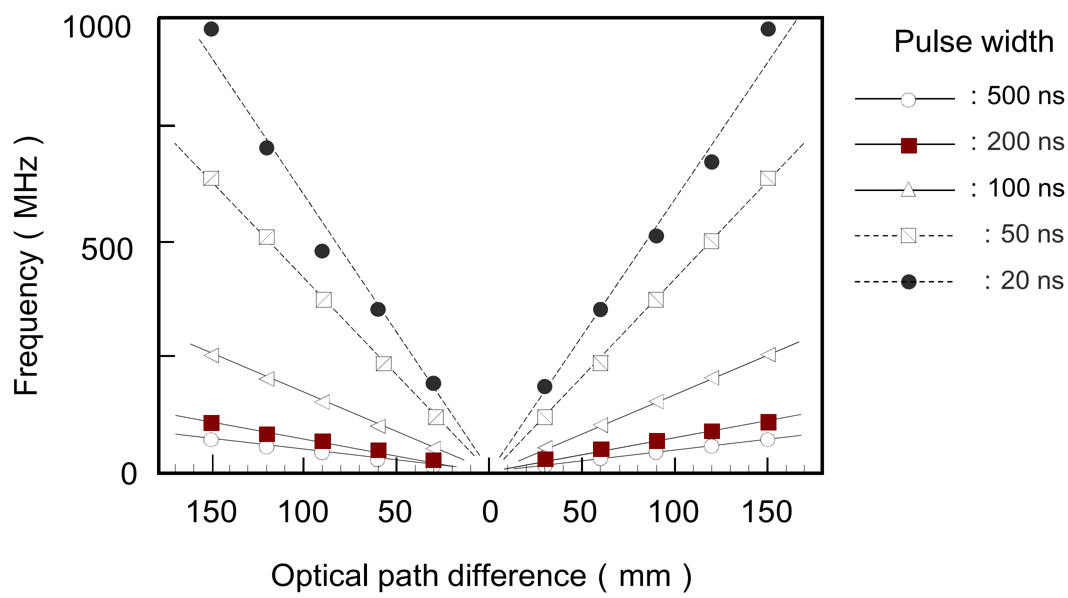


Fig. 16. Estimation of line length coincidence.

We are developing an advanced method to resolve the problem. Our new proposal is to deliberately shift the interference frequency. Figure 17 shows an advanced duplex optical fiber transmission system with frequency shifter. It equips an 80 MHz frequency shifter along the detour line. Other devices are the same as those described in Section 3.2.

We have conducted the same experiments with this advanced transmission system as before. We evaluated interference of the duplicated signals by changing the optical path difference with the optical line length adjuster.

Experimental results are shown in Figs. 18 and 19. Time-domain waveform of unified optical pulses indicates in Fig. 18 that signals along the detour and regular lines have interfered. A Fourier-transformation provided the frequency-domain characteristics of the interference as shown in Fig. 19. It reveals that each interfered waveform has the peak of spectrum power. In case the detour line length agrees with the regular line, the frequency of the peak power is 80 MHz which is as much as we have assigned with the frequency shifter.

An evaluation of the frequency of the peak power in terms of the optical path difference confirmed that the frequencies were proportional to the optical path difference as shown by white circles in Fig. 20, where the horizontal and vertical axes express the optical path difference and the frequency for the maximum power of Fourier-transformed spectrum, respectively.

Black circles in the figure represent the remainders of subtracting 80 MHz from the peak frequency. They also show the linearity as good as we obtained without the frequency filter.

If adopting this method, we can determine the optimal position where the line lengths coincide in high accuracy only by finding the specified value of the frequency shifter instead of extrapolation.

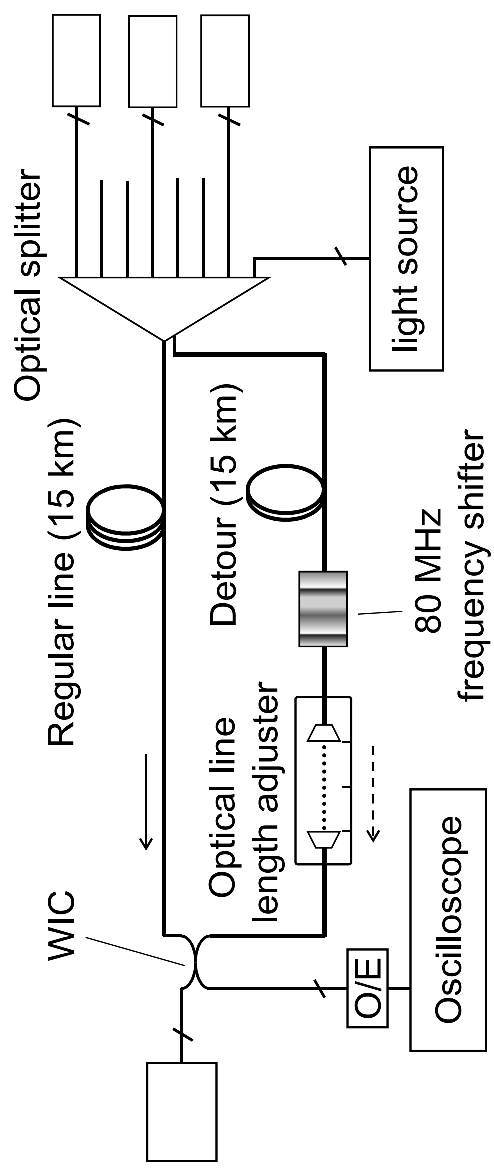
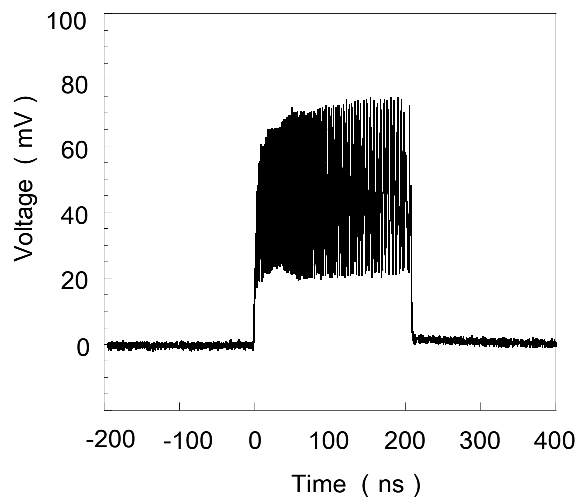
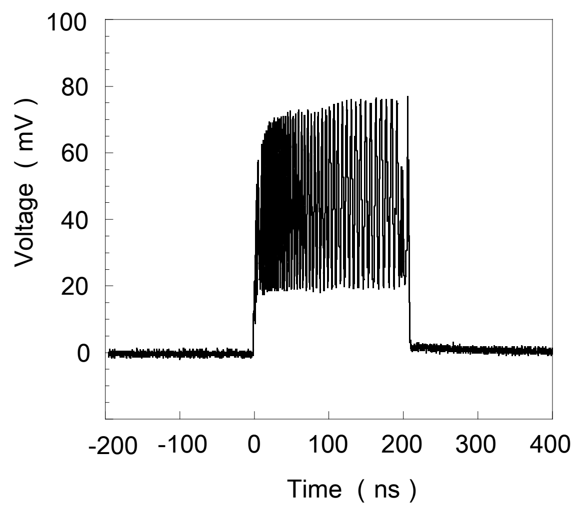


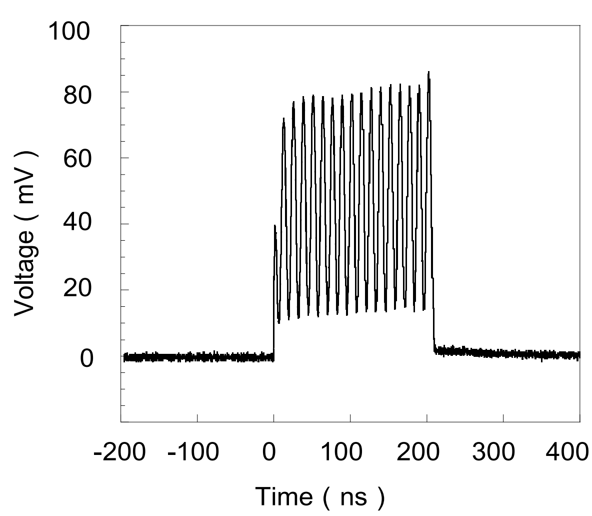
Fig. 17. Advanced duplex optical fiber transmission system with frequency shifter.



(a) Optical path difference 0.31 m.

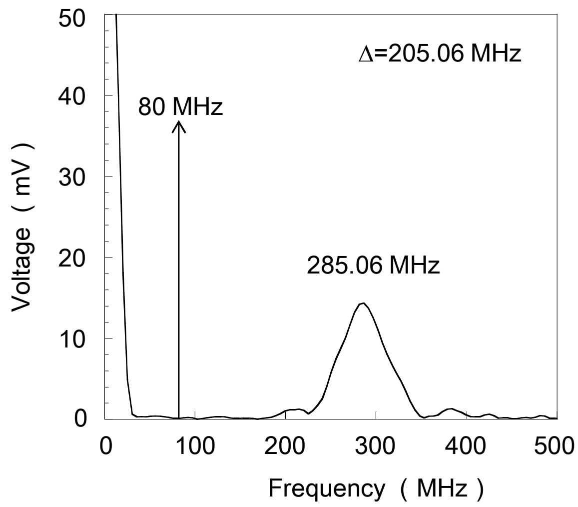


(b) Optical path difference 0.14 m.

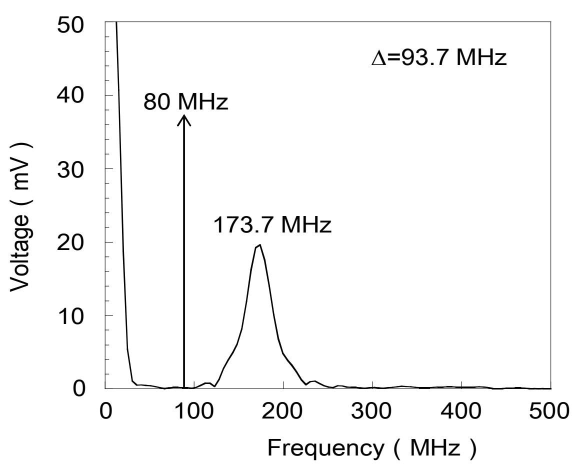


(c) Optical path difference 0 m.

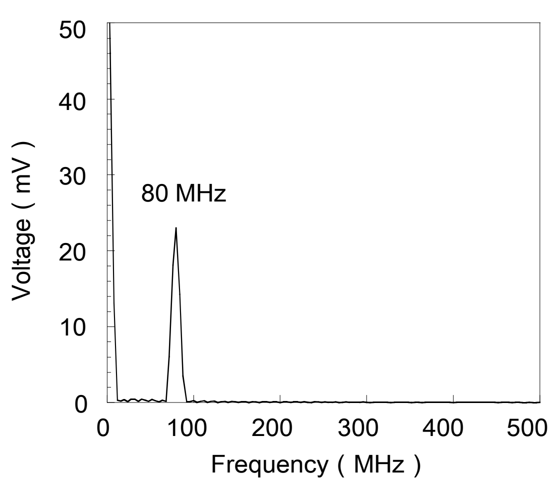
Fig. 18. Time-domain unified optical pulses.



(a) Optical path difference 0.31 m.



(b) Optical path difference 0.14 m.



(c) Optical path difference 0 m.

Fig. 19. Frequency-domain unified optical pulses.

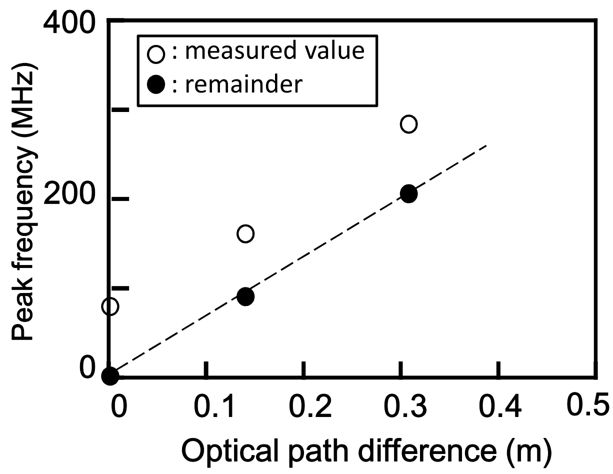


Fig. 20. Deterministic identification of line length coincidence.

6. Conclusion

This paper proposed the high-resolution optical line length measurement technique, which was applied to the switching method for optical transmission lines transferring live optical signals. The method exchanged optical fibers instead of using electric apparatus to control transmission speed.

We have disclosed the requirements for replacement of in-service optical transmission cables after investigating problems of the existing methods.

We next proposed the optical line switching technique and the optical cable replacement procedure that used duplex transmission lines. It was determined that the tolerance of the difference in duplex line length is 80 mm as for the GE-PON transmission system.

The optical line shunt system was designed, and its prototype was actually constructed. An optical line length adjuster, designed based on an FSO system, continuously lengthened the optical line up to 100 m with a resolution of 0.1 mm.

An optical line length measurement technique was investigated in detail by evaluating the duplicated test light pulses. As a result, it successfully identified the difference in length between the duplicated lines from 100 m to 10 mm. An interferometry measurement distinguished the difference between line lengths to an accuracy of better than 10 mm by analyzing interfering waveforms created by chirped laser pulses. This system was applied to a 15 km GE-PON network and succeeded in replacing the communication lines without inducing any frame loss.

We also discussed the improvement of line length measurement. It was suggested that the test light with narrow pulse width could give a higher sensitivity. If using the frequency shifter within the detour transmission line, we could identify the optimal position where the line lengths coincide in high accuracy without extrapolation.

7. References

Azuma, Y., Tanaka, K., Yoshida, K., Katayama, K., Tsujimura, T., & Shimizu, M. (2008). Basic investigation of new transfer method for optical access line, *IEICE Technical Report Japan*, OFT2008-52, (2008), pp. 27-31

Cao, S. C. & Cartledge, J.C. (2002). Measurement-Based Method for Characterizing the Intensity and Phase Modulation Properties of SOA-MZI Wavelength Converters, *IEEE Photonics Technology Letters*, Vol.14, No.11, (2002), pp.1578- 1580

Fukada, Y., Suzuki, K., Nakamura, H., Yoshimoto, N., & Tsubokawa, M. (2008). First demonstration of fast automatic-gain-control (AGC) PDFA for amplifying burst-mode PON upstream signal, *Proceedings of European Conference on Networks and Optical Communications 2008*, paper WE.2.F.4, 2008

Hornung, S., Wood, R., & Keeble, P. (1990). Single-mode optical networks to the home, *Proceedings of IEEE International Conference on Communications.*, vol. 4, pp. 1563-1571, April 1990

ITU-T Recommendation G.983.1 (1998). Broadband optical access systems based on Passive Optical Networks (PON), 1998

Sankawa, I., Yamamoto, F., Okumura, Y., & Ogura, Y. (2006). Cost and quantity analysis of passive double-star optical-access-network facilities for broadband service multiplexing, *Journal of Lightwave Technolgy*, vol. 24, no. 10, (2006), pp. 3625-3634

Saunders, R.A., King, J.P. & Hardcastle, I. (1994). Wideband chirp measurement technique for high bit rate sources, *Electronics Letters,* Vol.30, No.16, (1994), pp. 1336-1338

Spilent Communications. (2011). *SmartBits,* Available from: http://www.spirent.com/Solutions-Directory/Smartbits.aspx

Tanaka, K., & Horiuchi, Y. (2008). 1:N OLT Redundant Protection Architecture in Ethernet PON System, *Proceedings of Optical Fiber Communication Conference/ National Fiber Optic Engineers Conference*, pp. 1-6. San Diego, February 2008

Tanaka, K., Tsujimura, T., Yoshida, K., Katayama, K., & Azuma, Y. (2009). Frame-loss-free Line Switching Method for In-service Optical Access Network using Interferometry Line Length Measurement, *Proceedings of Optical Fiber Communication Conference 2009*, paper PDPD6, 2009

Tanaka, K., Zaima, M., Tachikura, M. & Nakamura, M. (2002). Downsized and enhanced optical fiber cable transfer splicing system, *Proceedings of 51st International Wire and Cable Symposium*, November 2002

Torregrosa, A. J. et al. (2007). Return-to-Zero Pulse Generators Using Overdriven Amplitude Modulators at One Fourth of the Data Rate, *IEEE Photonics Technology Letters*, Vol.19, No.22, (2007), pp.1837- 1839

Tsujimura, T., Tanaka, K., Yoshida, K., Katayama, K., & Azuma, Y. (2009a). Infallible Layer-one Protection Switching Technique for Optical Fiber Network, *Proceedings of 14th European Conference on Networks and Optical Communications/ 4th Conference on Optical Cabling and Infrastructure*, 2009

Tsujimura, T., Yoshida, K., Tanaka, K., & Azuma, Y. (2010). Transmission length measurement for error-free optical fiber line switching system, *Proceedings of International Conference on Networked Sensing Systems*, pp. 149-152, 2010

Tsujimura, T., Yoshida, K., Tanaka, K., Katayama, K., & Azuma, Y. (2009b). Interruption-free Shunt System for Fiber Optics Transmission Line, *SICE Transactions on Industrial Application,* Vol. 8, No. 16, (2009), pp. 125-131

Watanabe, I., Saito, H., Kobayashi, H., & Takashima, S. (1992). Subscriber optical fiber cable transfer splicing using mechanically transferable connectors, *IEEE Journal of Lightwave Technology*, Vol. 10, No. 6, (June, 1992), pp. 720-727

Willebrand, H. et al. (1999), *Free-Space Optics*, Sams Publishing

Xu, D. J., Yen, W., & Ho, E. (2001). Proposal of a New Protection Mechanism for ATM PON Interface, *Proceedings of IEEE International Conference on Communications*, Vol. 7, pp. 2160-2165, 2001

Yoshida, K., & Tsujimura, T. (2010). Seamless Transmission Between Single-mode Optical Fibers Using Free Space Optics System, *SICE Journal of Control Measurement and System Integration*, Vol. 3, No. 2, (2010), pp.94-100

Yoshida, K., Tanaka, K., & Tsujimura, T. (2011). Robotic Waveguide by Free Space Optics, In: *Advances in Mechatronics,* Martínez-Alfaro, H., InTech, ISBN 978-953-307-373-6

Yoshida, K., Tanaka, K., Katayama, K., Tsujimura, T., & Azuma, Y. (2009). Collimator Focus Adjustment for Free Space Optics System Using Single-mode Optical Fiber, *Proceedings of ICROS-SICE International Joint Conference,* pp. 1338-1341, 2009

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This book provides the most recent studies on interferometry and its applications in science and technology. It is an outline of theoretical and experimental aspects of interferometry and their applications. The book is divided in two sections. The first one is an overview of different interferometry techniques and their general applications, while the second section is devoted to more specific interferometry applications comprising from interferometry for magnetic fusion plasmas to interferometry in wireless networks. The book is an excellent reference of current interferometry applications in science and technology. It offers the opportunity to increase our knowledge about interferometry and encourage researchers in development of new applications.