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Robotic Waveguide by Free Space Optics

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1. Introduction

Road construction and work on the water supply often require the relocation of aerial/underground telecommunication cables. 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. Customers expect real-time transmission for high-quality communications to continue uninterrupted, especially for video transmission services.

Some 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 [1] has been developed to minimize the disconnection time. It takes 30 ms to switch a transmission line, and more than 2 seconds * to restore communications with, for example, GE-PON [2].

We 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 [3, 4]. Two essential techniques were presented; a measurement method and a system for adjusting the transmission line length. The latter continuously lengthens/shortens the line over very long distances without losing transmitted data based on free space optics (FSO). The former distinguishes the difference between the duplicated line lengths by analyzing signal interference. The mechanism that automatically coordinates both these two functions and referred to as a robotic waveguide in this paper compensates for the traveling time difference of a transmitted pulse. 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 [5-7]. We have applied the technique to measure length of several kilometers of optical fibers with a 10 mm resolution.

This paper describes the design of our robotic waveguide system. An optical line length measurement method is studied to distinguish the difference of two lines by evaluating interfered optical pulses. An optical line switching procedure is designed, and a line length adjustment system is prototyped. Finally, we applied the proposed system 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.

2. Optical line duplication for switching over

Figure 1 shows an individual optical line in a GE-PON transmission system with a single star configuration. Optical pulse signals at two wavelengths are bidirectionally transmitted through a regular line between customers' ONU and an OLT in a telephone office via a wavelength independent optical coupler, WIC1, and a 2x2 optical splitter, 2x2 SP, respectively.

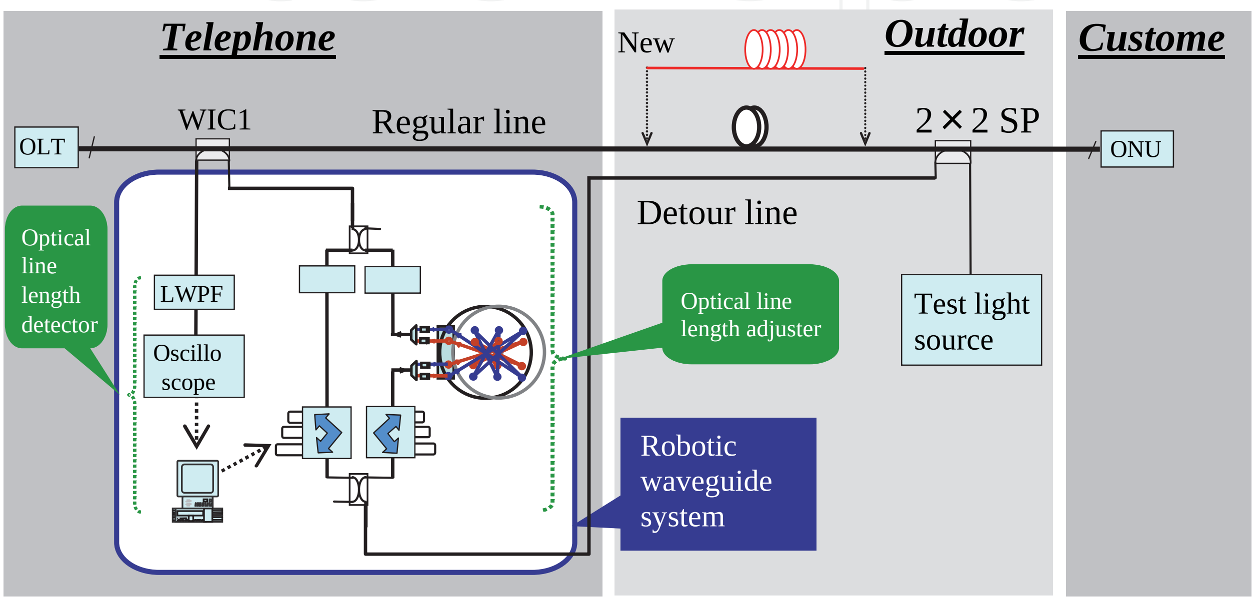


Fig. 1. Robotic waveguide system for optical fiber transmission line.

We have designed a robotic waveguide system, and a switching procedure for three wavelengths, namely 1310 and 1490 nm for GE-PON transmission, and 1650 nm for measurement. A robotic waveguide system is installed in a telephone office. It is composed of an optical line length detector and an optical line length adjuster. 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. 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. Some optical switches (SWs) and optical fiber selectors (FSs) control the flow of the optical signals managed by a controller. The optical pulses are compensated by 1650 and 1310/1490 nm amplifiers [8]. The proposed method temporarily provides a duplicate transmission line as shown in Fig. 1 to replace optical fiber cables. A detour line is prepared in advance through which to divert signals while the existing line is replaced with a new one. 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.

Experiments determined that the tolerance of the difference in line length is 80 mm with regard to the GE-PON transmission system.
The proposed system controls the adjustment procedure so that the difference in length between the detour and regular lines is adjusted within 80 mm.

3. Optical line length difference detection

We use laser pulses at a wavelength of 1650 mm to detect the optical path length difference. 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

$$\Delta L = c \cdot \Delta t / n, \tag{1}$$

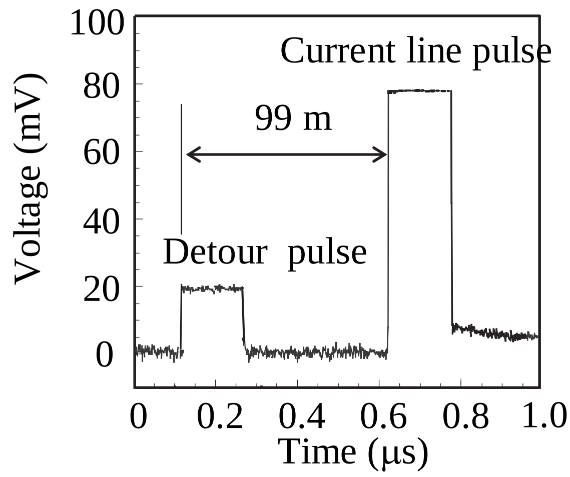
where c is the speed of light, Δt is the difference between the signal arrival times for the regular and detour lines, and n is the refractive index of optical fiber.
Figure 2 shows the received pulses observed with an oscilloscope. When the detour is 99 m shorter than the active line, pulses traveling through the detour line reach the oscilloscope about 500 ns earlier than through the regular line. The former pulse approaches the latter as shown in Fig. 2(b), while the system lengthens the detour line using the optical path length adjuster. This method fails if the difference between the line lengths is less than 1 m, because the two pulses combine as shown in Fig. 2(c).
We also 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 when the optical pulses combine. A chirped light source generates interference in the waveform of a unified pulse.
Each pulse, $E(L_j, t)$ is expressed as

$$E(L_j, t) = A_j \exp[-i(k \cdot n \cdot L_j - \omega_j \cdot t + \phi_0)], \tag{2}$$

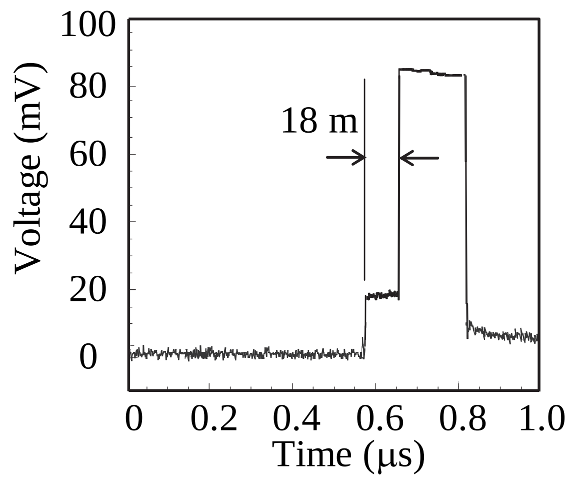
where j represents the regular line, 1, or the detour line, 2. And, A_j, k, n, L_j, ω_j, t, ϕ_0 denote amplitude, wavenumber in a vacuum, refractive index of optical fiber, line length, frequency, time, and initial phase, respectively. The intensity of a waveform with interference, I, is calculated by taking the square sum as

$$I = |E(L_1, t) + E(L_2, t)|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(k \cdot n \cdot \Delta L - \Delta\omega \cdot t), \tag{3}$$

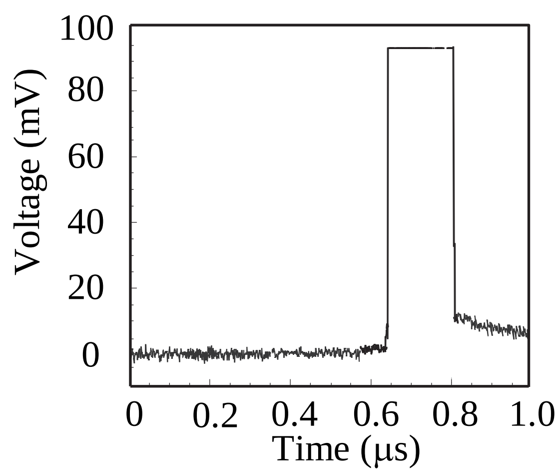
where ΔL and $\Delta\omega$ represent the differences between line lengths and frequencies, respectively.
The waveform with interference depends on the delay between the pulses' arrival times. Time-domain waveforms are shown in Fig. 3. When the gap was 0.5 m, the waveform contained high-frequency waves as shown in Fig. 3(a). The less the gap became, the lower-frequency the interfered waveform was composed of. When the lengths of two lines coincided, a quite low-frequency waveform was observed as Fig. 3(d).



(a) 99 m apart



(b) 18 m apart



(c) 1 m apart

Fig. 2. Time-domain optical line length measurement when difference in line length is more than 1 m.

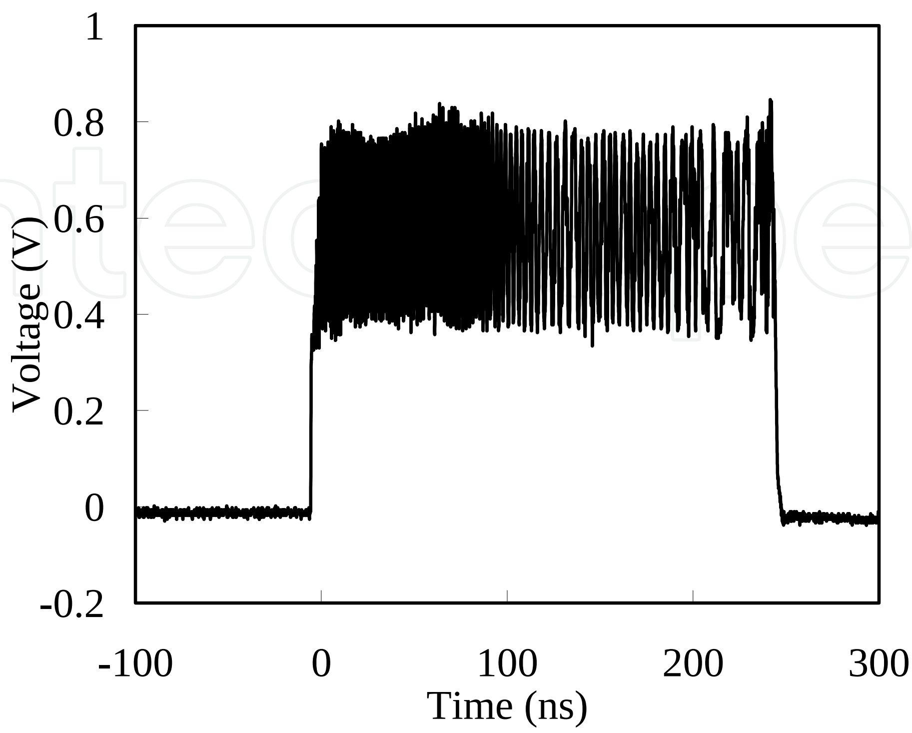


Fig. 3. (a) 0.5 m apart

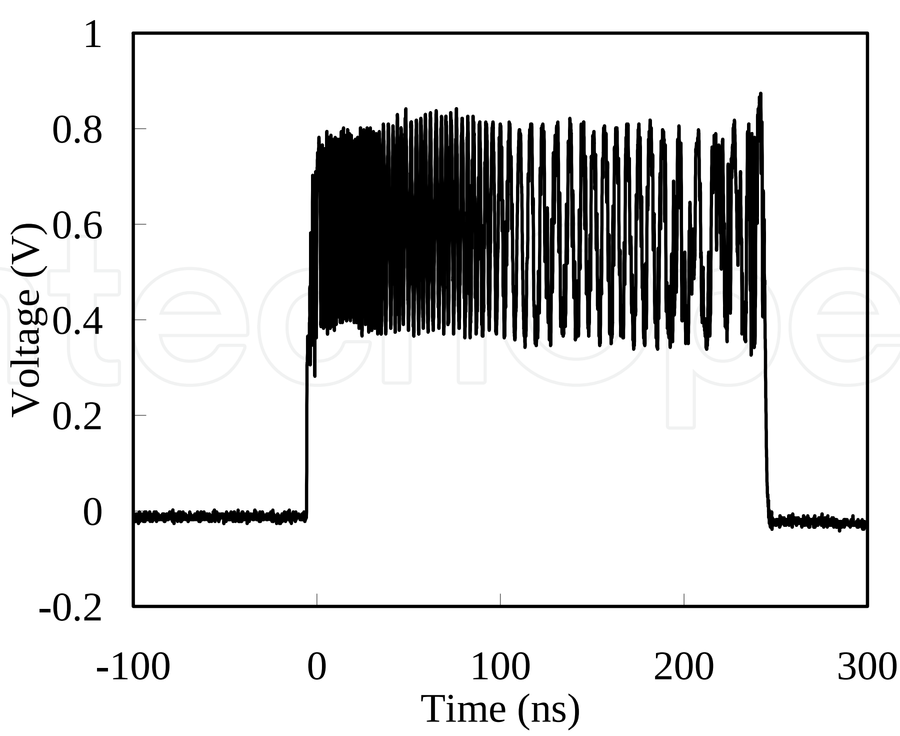


Fig. 3. (b) 0.3 m apart

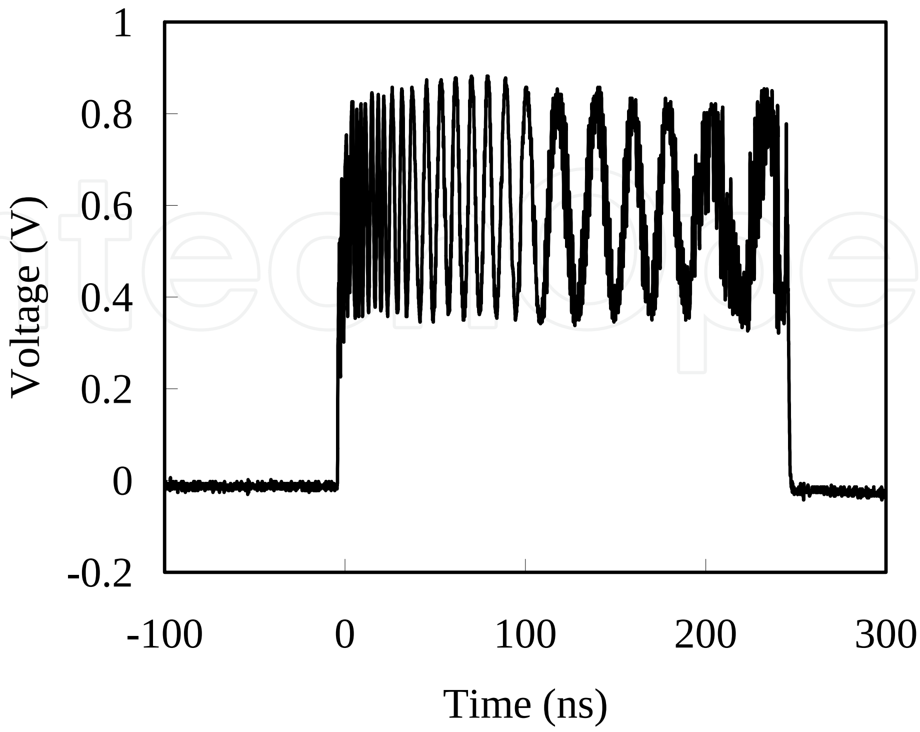


Fig. 3. (c) 0.1 m apart

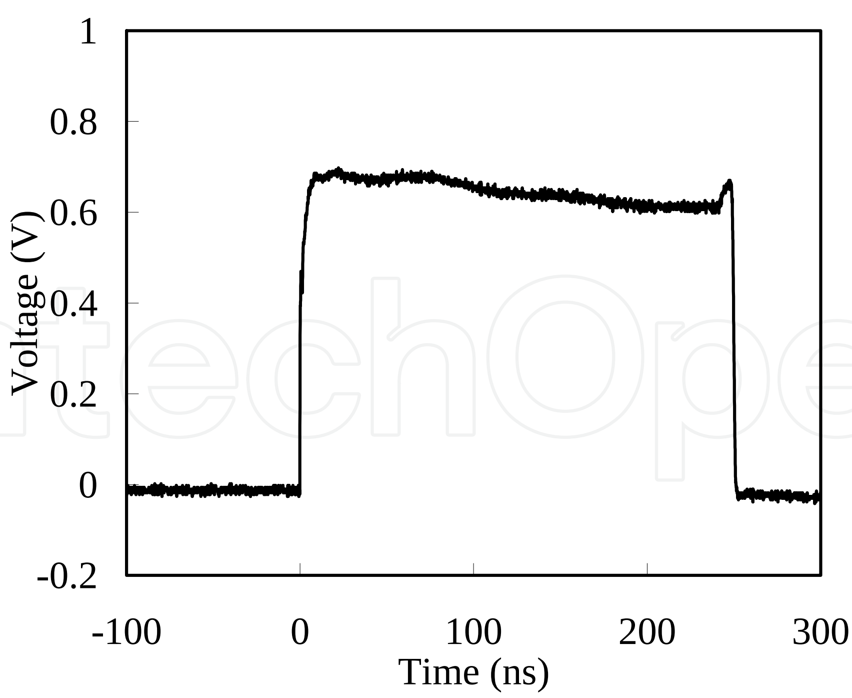


Fig. 3. (d) 0 m apart

Fig. 3. Time-domain optical line length measurement when difference in line length is less than 1 m.

A Fourier-transform spectrum reveals the characteristics. When the gap was 0.5 m, the waveform with interference was composed of the power spectrum shown in Fig. 4(a). The peak power indicated that the major frequency component was around 600 MHz. Figure 4(b) and (c) indicate that the peak powers for gaps of 0.3 and 0.1 m were 360 and 120 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. 4(d).

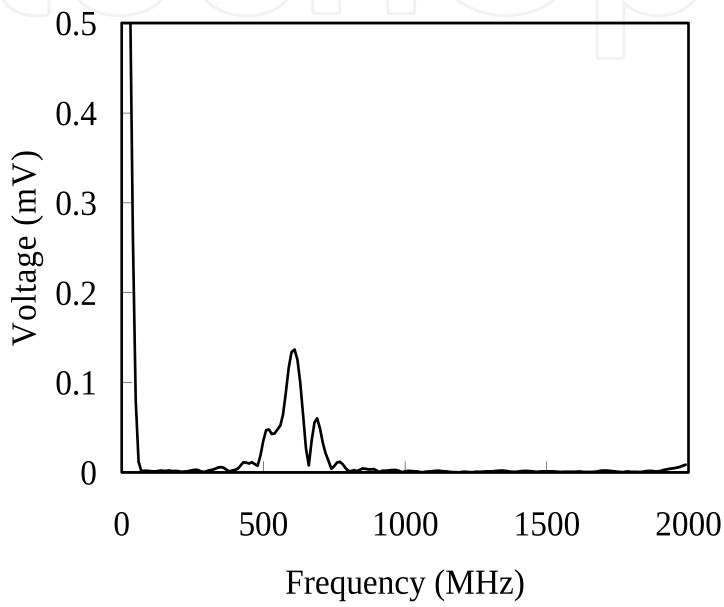


Fig. 4. (a) 0.5 m apart

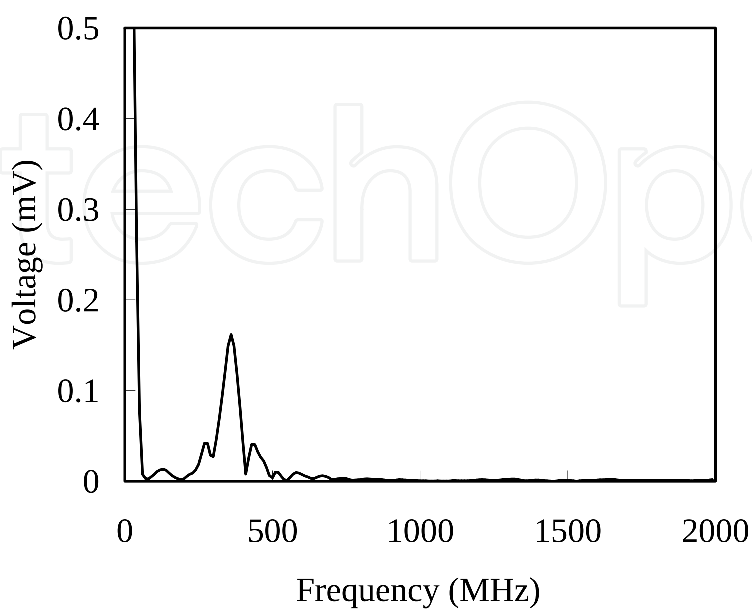


Fig. 4. (b) 0.3 m apart

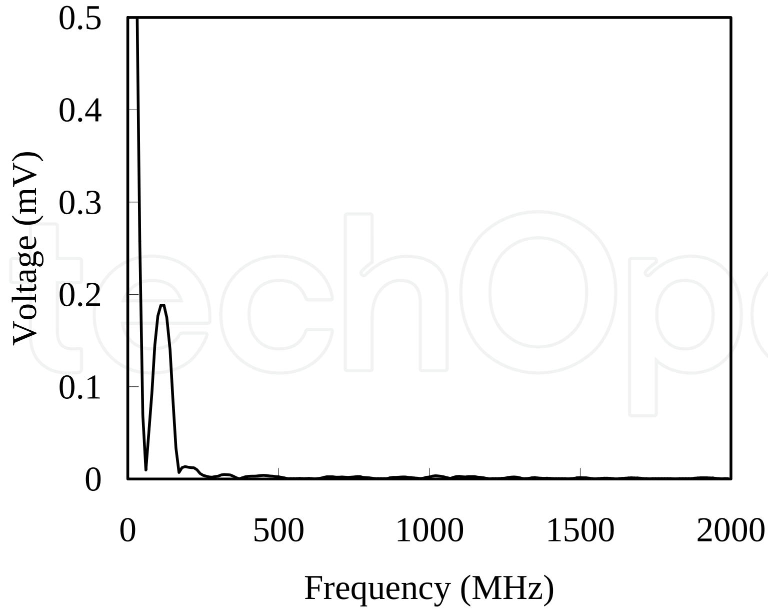


Fig. 4. (c) 0.1 m apart

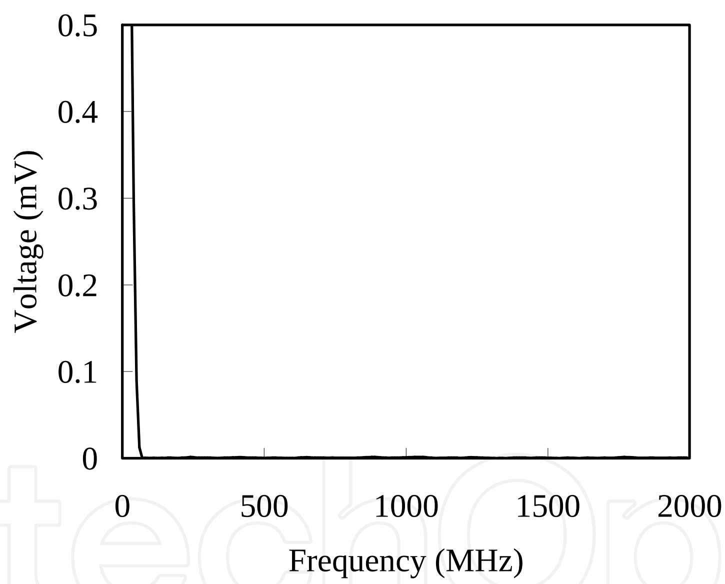


Fig. 4. (d) 0 m apart

Fig. 4. Frequency-domain optical line length measurement.

An evaluation of the frequency characteristics in the interfered waveforms showed that the peak frequencies are proportional to the difference between the line lengths from -1 to 1 m as shown in Fig. 5. 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.

We have 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.

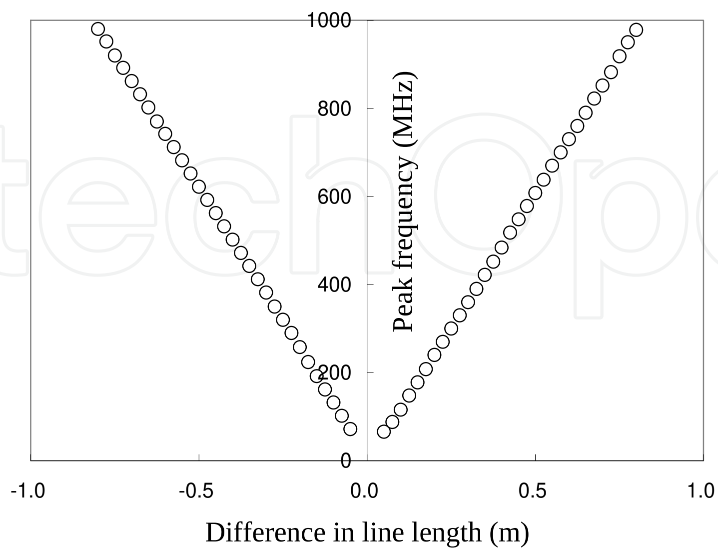


Fig. 5. Estimation of line length coincidence.

4. Robotic waveguide system

We designed a prototype of the robotic waveguide system to apply to a GE-PON optical fiber line replacement according to the procedure described below.

An optical line length adjuster, shown in Photo 1, is installed along the detour line. The adjuster is equipped with two retroreflectors, which directly face each other as shown in Fig. 6. A retroreflector consists of three plane mirrors, each of which is placed at right angles to the other two. And it accurately reflects an incident beam in the opposite direction regardless of its original direction, but with an offset distance. The vertex of the three mirrors in the retroreflector is in the middle of a common perpendicular of the axes of the incoming and outgoing beams as shown in Fig. 6. The number of reflections is determined based on the retroreflector arrangement. A laser beam travels 10 times between the retroreflectors in our prototype, and are introduced into the other optical fiber. Optical pulses are transmitted through an optical fiber, divided into three wavelengths by wavelength division multiplexing (WDM) couplers, and discharged separately into the air from collimators. The focuses of a pair of collimators corresponding for a wavelength is best tuned for the wavelength to achieve the minimum coupling loss. The collimators for multiple wavelenghts are arranged to share the two retroreflectors as shown in Fig. 7.

The detour line between the retroreflectors consists of an FSO system [9]. The detour line length can be easily adjusted by controlling the retroreflector interval with a resolution of 0.14 mm. 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, by $k\Delta x/n$, where k, Δx, n are the number of journeys between the retroreflectors, the retroreflector interval variation, and the refractive index of optical fiber, respectively. The FSO lengthens the optical line length up to L_0.

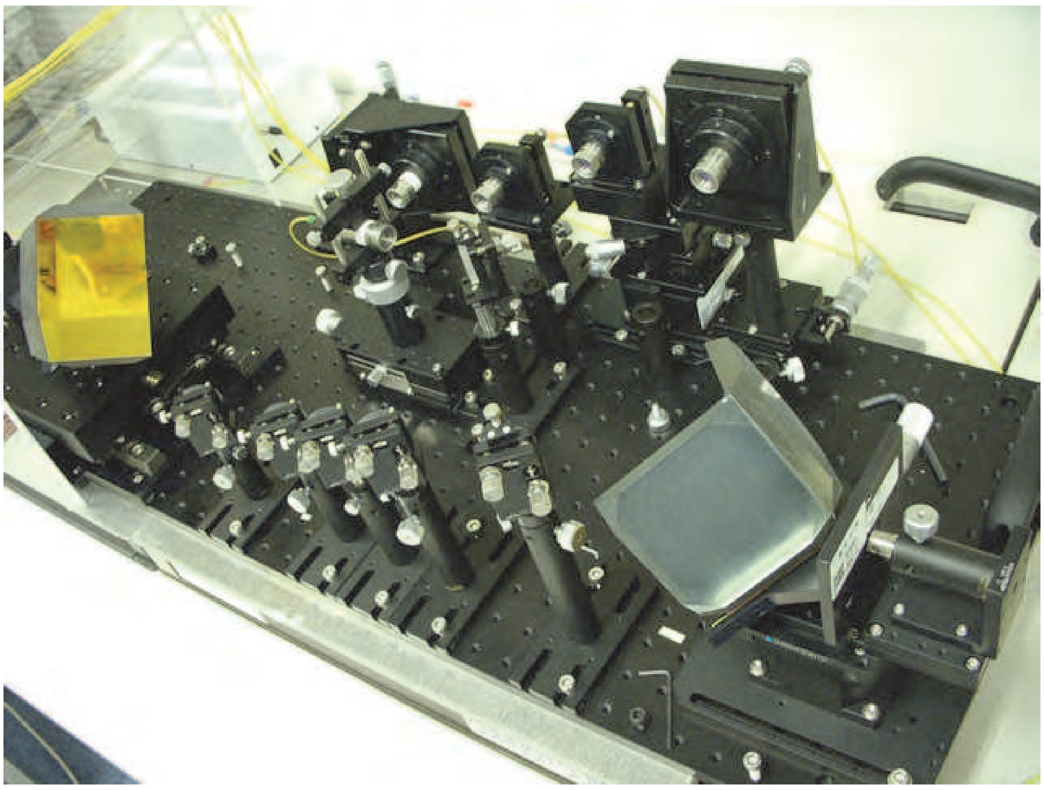


Photo 1. Free-space optics line length adjuster.

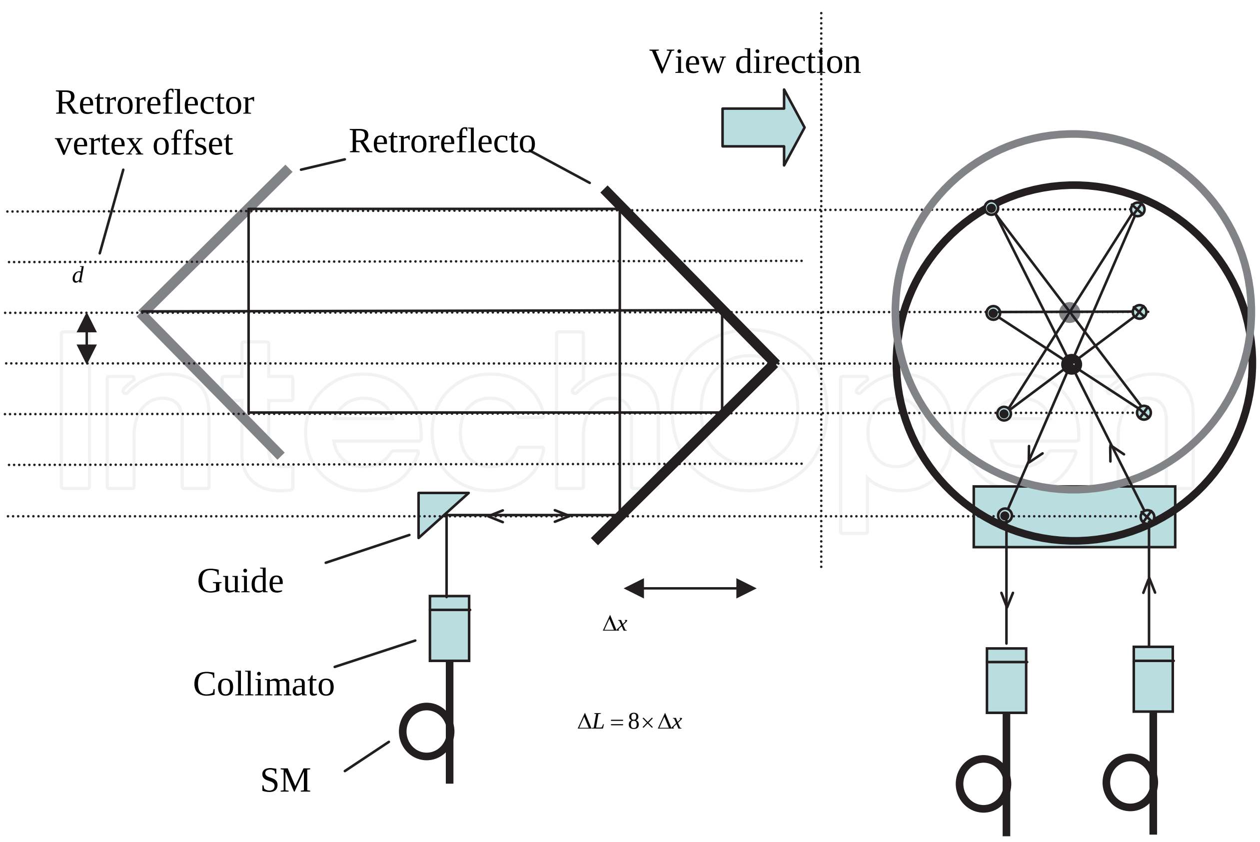


Fig. 6. Free-space optics line length adjuster.

$$L_0 = k\, \Delta x_{max} / n, \qquad (5)$$

where Δx_{max} is the maximum range of the retroreflector interval variation. The maximum range of our prototype, Δx_{max}, is around 0.3 m, the refractive index, n, of the optical fiber is 1.46, the number of journeys, k is 10, and the optical line span, L_0, tuned by the adjuster is 2 m.

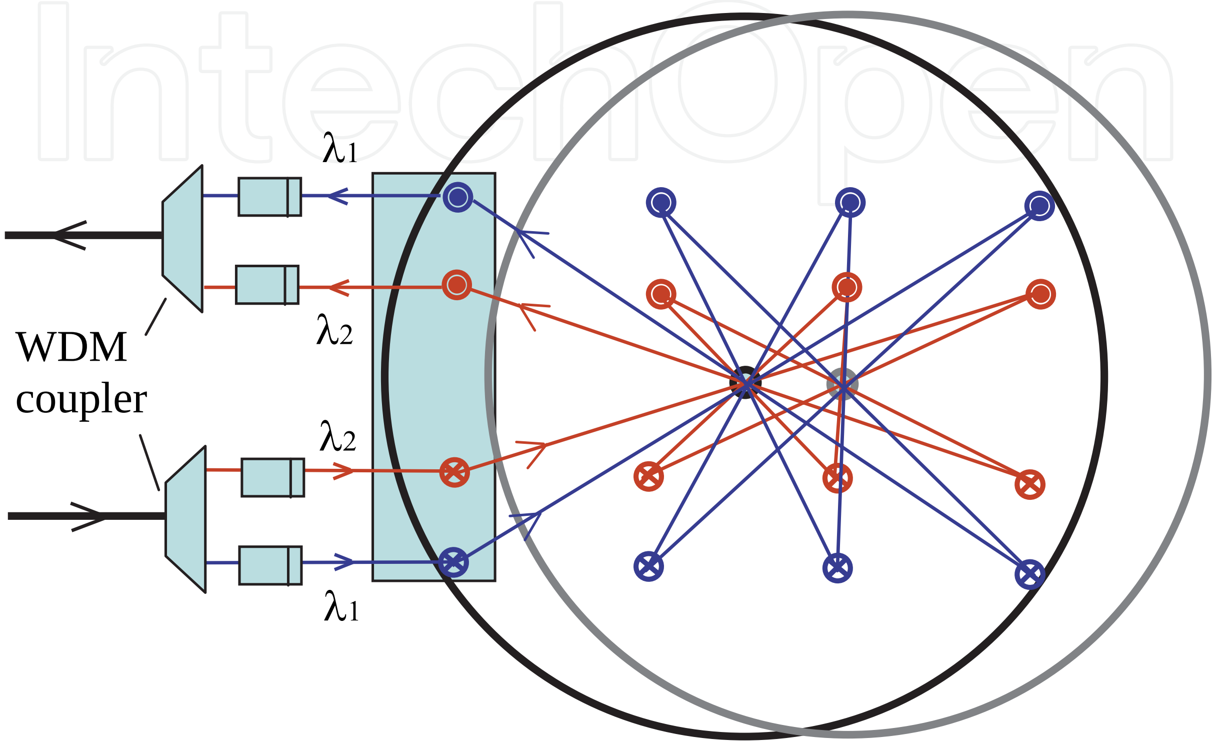


Fig. 7. Collimator arrangement for use of multiple wavelengths.

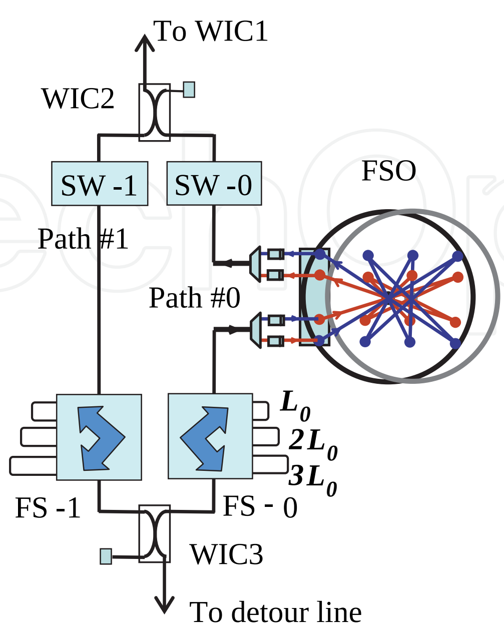


Fig. 8. FSO system with optical path length accumulation mechanism.

The limit of the adjustable range is a practical problem when this system is applied to several kilometers of access network. Therefore, we employ optical line length accumulators. The optical line length adjuster contains two optical paths, #0 and #1 as shown in Fig. 1 or Fig. 8. An optical switch and an optical fiber selector 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 following operation as 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 has selected an optical fiber of length L_0, the active line is switched from path #0 to path #1. The FSO system then returns to the origin, and the optical fiber selector 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 to repeat the same operation. In this way the adjuster accumulates spans extended by the FSO system. The scanning time of our prototype is 10 seconds, because the retroreflector operates at 30 mm/s.
The optical line length adjuster enables us to lengthen/shorten the detour line while continuing to transmit optical signals.

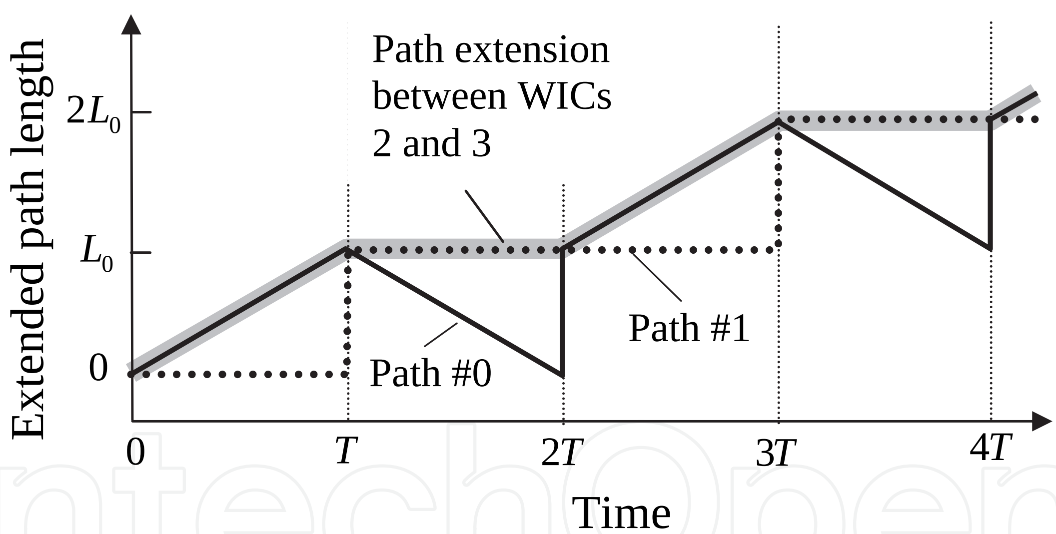


Fig. 9. Time chart of operation for optical path length accumulation.

5. Experiments on optical line replacement

The optical line replacement procedure, shown in Fig. 10 where a 2x8 optical splitter is used instead of a 2x2 splitter, is as follows:
1. A detour line is established between a WIC and a 2x8 optical splitter.
2. The detour line length is measured with a 1650 nm test light using an optical line length measuring technique, and is adjusted to the same length as the regular line using an optical line length adjusting technique. These techniques are described in the preceding sections.

3. Once the lengths of the two lines coincide, the transmission signals are also launched into the detour line.
4. The regular line is cut and replaced with a new line, while the signals are being transmitted through the detour line. A long-wavelength pass filter (LWPF) is temporarily installed in the new line.
5. 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 prevents only the optical transmission pulses from traveling through the new line.
6. The LWPF is then removed and the transmission is duplicated. The detour line is finally cut off.

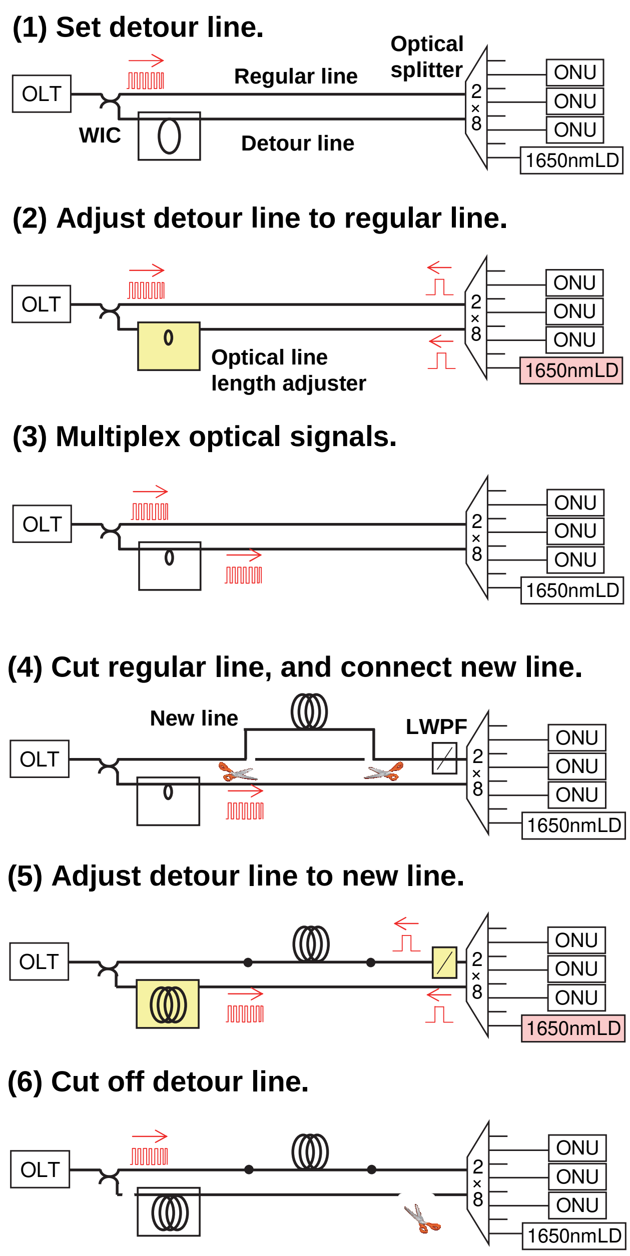


Fig. 10. Optical line replacement procedure.

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 severe when the method is applied to higher-speed communication services.
Next, we constructed a prototype of the robotic waveguide system shown in Fig. 1, and applied it to a 15 km GE-PON optical transmission line replacement. A 10 m optical fiber extension was added to the transmission line, while optical signals were switched between the duplicated lines during transmission.
Figure 11 shows the frame loss that occurred during optical line replacement, which we measured with a SmartBit network performance analyzer. No frame loss was observed at any switching stage if the difference between the duplicated line lengths was less than 80 mm. If the difference exceeded 80 mm, signal multiplexing caused frame loss in stages (a) and (d). We confirmed that the optical signals can be completely switched between the regular, detour, and new lines on condition that the line length is adjusted with sufficient accuracy.
The experimental results proved that our proposed system successfully relocated an in-service broadband network without any service interruption.

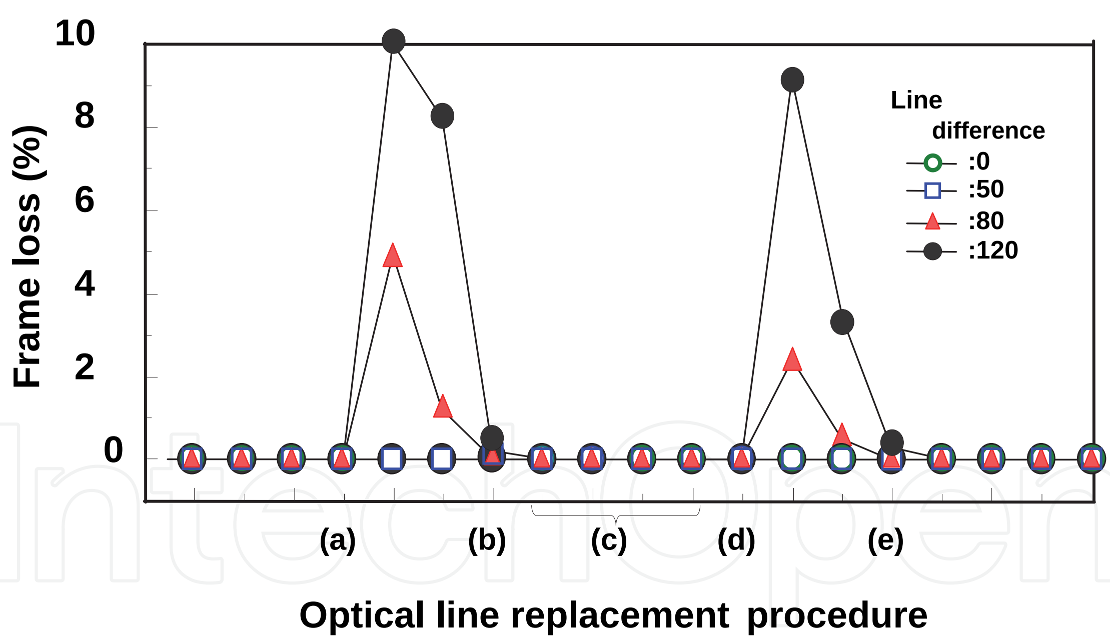


Fig. 11. Frame loss while replacing transmission line according to the procedure; (a) Multiplex signals of current line and detour line, (b) Cut current line, (c) Extend detour line, (d) Multiplex signals of detour line and new line, (e) Cut off detour line.

6. Conclusion

We proposed a new switching method for in-service optical transmission lines that transfers live optical signals. The method exchanges optical fibers instead of using electric apparatus to control transmission speed. The robotic waveguide system is designed to apply to duplicated optical lines. 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 successfully evaluated 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. We applied this system to a 15 km GE-PON network and succeeded in replacing the communication lines without inducing any frame loss.

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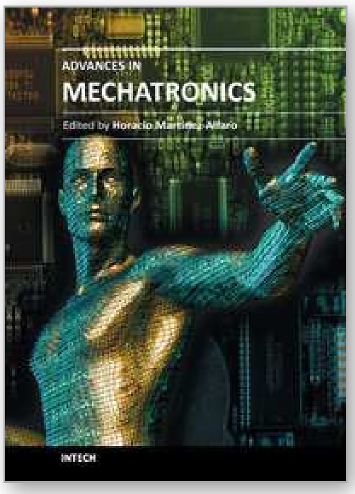

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