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1. Introduction

According to a significant *descoping* of the SDC detector to stay within the available budget, the number of readout channels of the straw-chamber outer tracker [1] was much reduced; it was about 140k channels in the final design. Originally we planned to install all the frontend electronics including the digitizer inside the calorimeter, in order to minimize the amount of cables passing through the calorimeter system. However, since the number of channels was not so huge in the final design, we thought that it would be possible to transfer all discriminator signals outside of the calorimeter through cables. This configuration, *digitizer-outside-the-calorimeter*, had many advantages; the digitizers need not be radiation-hard and, in general, relatively large space was available for them. The latter condition would make the packing and cooling of the digitizer electronics much less difficult.

In order to realize the *digitizer-outside-the-calorimeter* configuration, we needed to prove that the total amount of cables to be used for the signal transfer would fit within the available space inside of the gaps between the barrel and endcap calorimeters. As a reference, we now consider about a twisted-pair cable used for experiments at TRISTAN. The conductor of the cable is composed of 7 copper wires of

0.14 mm in diameter, equivalent to 27 AWG (American Wire Gage), and is covered with 0.25 mm-thick FEP insulator. Individually shielded 19 pairs of such cables are combined to form a bundle of 10 mm in diameter. This cable has good characteristics in cross talk, attenuation and frequency response, sufficient for transmitting analog signals of drift chambers up to several tens of meters.

If we use this cable for the SDC outer tracker, the total cross section of the cables amounts to at least $140\text{k}\times\pi\times(0.5\text{ cm})^2/19 = 5{,}800\text{ cm}^2$, *i.e.* $2{,}900\text{ cm}^2$ in each end. The area available in the calorimeter gap is about $6{,}600\text{ cm}^2$ in each end. All cables as well as pipes needed for the trackers placed inside of the calorimeter pass through this area, and about 1/4 of the space is occupied by the optical fibers of the endcap electromagnetic calorimeter. Therefore, the space available for the signal cables of the outer tracker would not be larger than 1/4 of the total area. Further, we have to take into account the packing density of the cables. Taking some safety factor into consideration, we had to make the thickness of the outer-tracker cables be at least one half of the cable referred above.

In order to study the feasibility of thinner cables, we fabricated and tested two types of very compact cables. One of them is a natural extension of the cable used at TRISTAN, a twisted-pair cable with thinner conductor, and the other is a new type of cable, a long and thin flat-ribbon cable. The structure of the fabricated cables and the results of the tests performed so far are presented in this report. In addition, the total thickness of the cables measured in radiation length, which may have caused a serious problem in our application, is estimated on the basis of the specification of these cables.

The development is incomplete since the SSC project demised before completion. However, the knowledge that we have collected through the development will be useful in designing the readout system of other presently planned or future detectors. The cable is one of the most low-tech parts in rapidly evolving modern electronics. The information described in this report will not become outdated in coming several years.

2. Twisted-pair cable

A thin twisted-pair cable (100 m long) was fabricated by Junkosha Co. The specification of the cable is listed in Table 1. The conductor of the cable is composed of 7 tin-plated copper wires of 0.079 mm in diameter (32 AWG). This conductor diameter was chosen because connectors are commercially available down to this size.

The conductors are covered with 0.12 mm-thick ETFE insulator. ETFE (ethylene tetrafluoroethylene copolymer) is known to have good mechanical properties as well as good electrical properties; $\varepsilon = 2.6$ and $\tan\delta = 0.005$ even in MHz range. Besides it is fire retardant, produces very small amount of smoke in fire and has superior radiation hardness. Good mechanical and electrical properties are preserved up to nearly 10 Mrad irradiation. The thickness of the insulator was minimized as far as sufficient mechanical strength could be maintained in the production process. Hence, the characteristic impedance was expected to be lower than ordinary twisted-pair cables.

Each twisted cable pair is shielded with aluminized polyester film, in order to eliminate the cross talk between pairs. The cable bundle comprises 19 such shielded pairs with a structure shown in Fig. 1. The bundle is further shielded with aluminized polyester film and sheathed with PVC. Two drain wires are inserted in each bundle for external connection for the shields. The diameter of the finished bundle is only 6 to 7 mm. The cross section is less than one half of the cable used at TRISTAN. Therefore, this cable satisfies the requirement on the size. The total size can be further reduced if we adopt a bundle with larger number of cable pairs, since the overhead with the sheath is significant.

Electrical property of the cable was measured by Junkosha. The measurements were done on 5 pairs in a 10 m-long sample of the fabricated bundle. The setup for the measurements is schematically shown in Fig. 2 and the results are summarized in Table 2. The characteristic impedance was found to be about 70 Ω and its variation was within ±5%. The signal attenuation was approximately 0.5 dB/m at 50 MHz. Since the rise time of the discriminator signal will be a few to ten nano seconds, the bandwidth of the signal would be around 50 MHz or narrower. Therefore, we expect that the signal attenuation should be at most 30% for a typical cable length of 5 m. This would be sufficient for our use. The signal propagation delay is 4.9 ns/m, corresponding to a velocity of 20 cm/ns.

The measurements can be compared with calculations described in ref. [2]. The estimated characteristic impedance is 76 Ω for the round-shape shield and 61 Ω for the race-track-like shield. The reality must be in-between. In fact the measurement, 70 Ω, lies between these estimates. The results for the signal attenuation are plotted in Fig. 3 as a function of signal frequency. Curves drawn in the figure show the predictions obtained by rescaling the values for 100 Ω cables [2] to the three impedance values: 61, 70 and 76 Ω. The predictions roughly reproduce the measurements.

Measurements were also carried out at KEK by using typical square wave signals as input. The setup is shown in Fig. 4, where an ECL line-driver (10192) provided the input signal and the transmitted signal was received by a differential amplifier (TL592). The differential signal lines were terminated at both ends with two 36 Ω resisters. A 4.5 m-long sample of the cable bundle was used for the measurement. The input signal was measured by connecting the line-driver and the receiver with short cables. The input and output signal shapes are shown in Fig. 5. The attenuation was found to be 12%, which is in a reasonable agreement with the expectation. The cross talk was also measured between typical pairs and was found to be always smaller than 1%.

3. Flat-ribbon cable

A new type of cable, a long and thin flat-ribbon cable, was fabricated by Hitachi Cable Corp. The structure of the cable is illustrated in Fig. 6. Copper conductors, 50 μm-thick and 0.5 mm-wide, are placed with a pitch of 0.8 mm. The conductors are sandwiched with Kapton films coated with polyester-base glue. These materials are heat-pressed to form a flat cable. Before making the cable structure, windows are cut out periodically on one of the Kapton films. External connection is allowed at both ends by cutting the continuously produced cable at the windows. The distance between the windows can be specified at any value, according to the required cable length. We chose a length of 4.5 m for the present test. The end structure of the cable is the same as ordinary flexible printed circuits (FPC), so that a wide variety of connectors are commercially available.

The structure described above is the original structure of this type of cables. Such cables are widely used in printers and image scanners to connect a moving head with a control circuit. In ordinary use, each cable is at most several 10 cm long and the signal frequency is not very high. Cross talk and noise pick-up do not cause a serious problem in such use. However, in our application, the cables are relatively long, typically 5 m. Furthermore, since the available space is limited, the cables must be tightly packed. The interference between cables could become a serious problem with the original structure.

From these concerns, we added a 9 μm-thick copper sheet and a covering film to the original structure, as shown in Fig. 4. The total thickness of the fabricated cable is about 220 μm. If we use this cable in differential mode, the cross section occupied by each signal channel is $2 \times 0.8\ \text{mm} \times 0.22\ \text{mm} = 0.35\ \text{mm}^2$. The cross section of the cable used at TRISTAN is about 4 mm^2 per channel. Therefore, with this flat-ribbon cable, we can achieve a reduction of more than one order of magnitude in the cable cross section. This is far better than the required value.

The fabricated cable is 4.5 m long and 2.5 cm wide, containing 30 conductors. Property of the cable was measured at KEK. The characteristic impedance was measured with a setup similar to that shown in Fig. 2a. The measured impedance is 10 Ω between the conductor and the shield, and 20 Ω between neighboring conductors. Since the distance between the conductors and the shield is very small, about 60 μm, the capacitance between them is very large and far larger than the capacitance between the conductors.

The attenuation was measured with the setup shown in Fig. 7 (a). The setup was the same as Fig. 4, except that the terminators were replaced with 10 Ω resisters, and the signals were measured directly on the signal line through a 1 kΩ resister and a 50 Ω coaxial cable. The observed signal shapes are shown in Fig. 8, and the signal attenuation was measured to be about 50%. We worried that a ringing seen in the observed signal shape might be caused by an interference between the conductors, because the cable was wound and tied compactly. However, no visible change was observed in the signal shape when we untied and widely spread the cable.

The cross talk was measured with the setup shown in Fig. 7 (b), and found to be nearly 2% between neighboring pairs. It decreased to about 1% when a ground line was interleaved between the pairs. A part of the cross talk may have originated in the connectors and the wiring in the measurement circuit, because small connectors for FPCs were used.

4. Thickness in radiation length

The material thickness of the cables measured in radiation length was an important number to be considered carefully, since the cables were planned to run inside of the electromagnetic calorimeters and a part of them run in front of the intermediate trackers (ITD). Figure 9 shows probable cable paths in the tracking volume. In the figure, the paths that may affect the tracking by ITD are drawn with solid lines, while the parts that would not affect the tracking are drawn with dashed lines. The radiation length was estimated as a function of the pseudorapidity (η) for the particles produced at the interaction point.

In the estimation for the thin twisted-pair cable, we assumed a use of 61-pair bundles. The cross section of the copper conductor (32 AWG) is 0.0343 mm^2 per cable. The cross section of the ETFE insulator and the sheath amounts to 35 mm^2 per bundle, if the sheath thickness is 0.5 mm. If the radiation length of these materials is comparable to ordinary plastics, about 15 times the radiation length of copper, the cross section is equivalent to 2.3 mm^2 of copper. Therefore the overall cable material is $61 \times 2 \times 0.0343 + 2.3 = 6.5$ mm^2 copper-equivalent per bundle.

We assumed that 4 cable bundles would be used for each trigger module (212 channels) and 3 bundles for each stereo module (159 channels). The total material thickness, calculated on the basis of these estimations and the module count presented in the SDC Technical Design Report [3], is shown in Fig. 10. The result shown with the solid line corresponds to the cable paths drawn with solid lines in Fig. 9, and the dashed line shows the total thickness including the paths drawn with dashed lines. The average thickness is nearly 20 % of the radiation length in the angular region, $1.7 \lesssim \eta \lesssim 1.95$.

A rough estimation was also carried out for the thin flat-ribbon cable. In this case, the cross section of copper is 0.064 mm^2 per channel (pair) including the shield plane. The cross section of the plastics is 0.27 mm^2 per channel, which corresponds to approximately 0.018 mm^2 of copper. Therefore, the total cross section is 0.082 mm^2 copper-equivalent per channel. This is about 75% of the estimation for the prototype twisted-pair cable. The ratio almost corresponds with that of the conductor cross section; 0.0343 mm^2 in the twisted-pair cable and 0.025 mm^2 in the flat-ribbon cable.

5. Summary and discussion

We have prototyped two types of compact cables, aiming at the use for the SDC straw-chamber outer tracker readout in the *digitizer-outside-the-calorimeter* configuration. One of them is a thin twisted-pair cable and the other is a thin flat-ribbon cable.

The twisted-pair cable has a 32 AWG conductor (7×0.079 mm^{ϕ}-wires), and individually shielded 19 pairs of the cables are combined to form a bundle of 7 mm (maximum) in diameter. The measured impedance is 70 Ω. This is smaller than ordinary twisted-pair cables since we have minimized the insulator thickness in order to reduce the cable volume. The signal attenuation has been measured as a function of signal frequency; it is about 0.5 dB/m at 50 MHz. The attenuation and the cross talk between pairs were also measured for square wave signals. The measured properties were sufficiently good for our application, and they were in a reasonable agreement with predictions calculated with known formulae and data.

The thickness of the twisted-pair cable, about 1/2 of typical such cables in cross section, is small enough to fit inside the space available for cabling. However, the thickness in radiation length could be a problem. The estimated thickness amounts to nearly 20% of the radiation length in the pseudorapidity region, $1.7 \lesssim \eta \lesssim 1.95$. The manufacturer can provide thinner cables down to 36 AWG (7×0.051 mm^{ϕ}-wires) as their regular products. However, adopting such cables, a problem will arise in the cable connection, since no connector is commercially available. We will have to adopt a non-standard way for the connection; for example, direct soldering onto circuit boards. Besides, for such very thin cables, the conductor material has to be replaced with a tin-copper alloy in order to preserve required mechanical strength. As a result, the conductivity will decrease and eventually the attenuation will become larger, although the degradation may not be so large.

The thin flat-ribbon cable is a new type of cable, in which flat copper conductors placed in parallel with 0.8 mm pitch are sandwiched by Kapton films coated with polyester-base glue. A thin copper layer is attached on one side of the cable, in order to shield the conductors against external noise and interference between cables.

This cable is very compact, about 1/10 of ordinary twisted-pair cables in cross section, and a wide variety of connectors are available since the cable geometry is chosen to be the same as ordinary FPCs. The impedance of the cable, 20 Ω between neighboring conductors, is rather low because the distance between the conductors and the shield is very small. The signal attenuation was measured to be about 50% and the cross talk between pairs to be at most a few percents, for a 4.5 m-long cable on square wave signals.

Although the measured properties were not unacceptable for our use, we have not measured some other basic properties of this flat-ribbon cable, such as frequency response and radiation hardness. Moreover, although the physical thickness is very small, the material thickness measured in radiation length is not very small; about 75% of the prototyped twisted-pair cable. It is possible to reduce it further by adopting a 0.5 mm-pitch cable, which Hitachi Cable can provide. Anyway, many things are still left to be examined before discussing the feasibility of this cable.

References

[1] B. Adrian *et al.*, *Conceptual Design Report for the Modular Straw Outer Tracking System*, IUHEE-91-10 and SDC-91-125 (1992);
See also ref. [3].

[2] Handbook of Cables (Junkosha, 1976), in Japanese.

[3] SDC Technical Design Report, SDC-92-201 and SSCL-SR-1215 (1992).

Table 1. The specification of the twisted-pair cable manufactured by Junkosha.

conductor	7×0.079 mm$^\phi$ tin-plated copper (32 AWG) 0.237 mm$^\phi$ in total, < 612 Ω/km (DC)
insulator	0.12 mm-thick ETFE
insulated individual cable	0.480 mm$^\phi$
shield of pair	aluminized polyester (Al on outer surface)
shielded pair	1.04 mm$^\phi$
number of pairs/bundle	19
drain wires	2×(7×0.079 mm$^\phi$ tin-plated copper)
shield of bundle	aluminized polyester (Al on inner surface)
sheath	0.5 mm-thick PVC
finished bundle	6.3 mm$^\phi$ (max. 7.0 mm$^\phi$)

Table 2. Results of the tests done by Junkosha.

test item (method)		unit	sample 1	2	3	4	5
impedance (TDR)		Ω	70.9	69.8	72.1	66.9	67.2
attenuation	10 MHz	dB	2.96	2.97	2.96	3.71	2.78
for 10 m	50 MHz		6.52	6.52	6.41	6.03	4.96
(NA)	100 MHz		9.74	9.78	9.74	8.72	8.22
propagation delay (TDR)		ns/m	4.89	4.88	4.92	4.89	4.86
propagation delay	10 MHz	ns/m	5.20	5.20	—	—	—
(NA)	50 MHz		5.11	5.04	—	—	—
	100 MHz		5.14	5.01	—	—	—

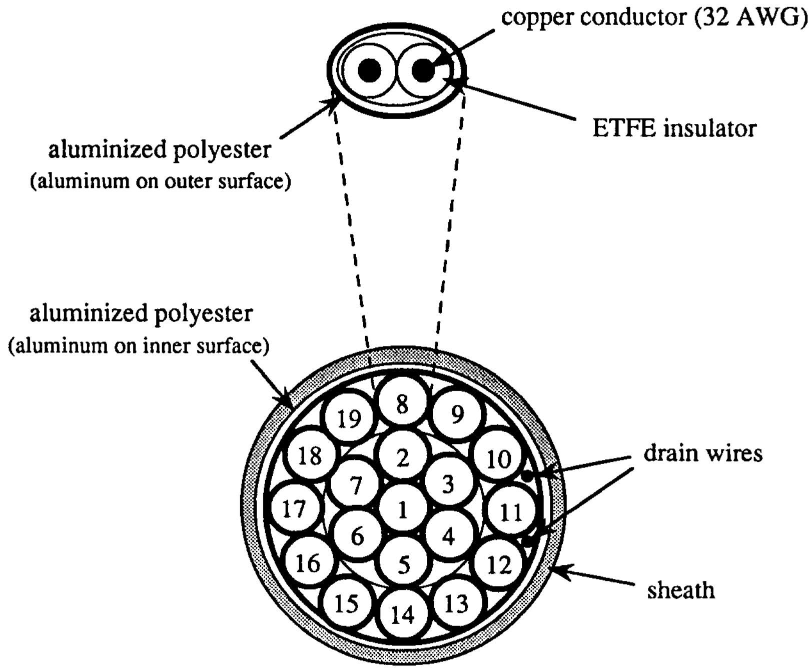

Fig. 1. The structure of the twisted-pair cable fabricated by Junkosha. The cable bundle is composed of individually shielded 19 pairs of cables.

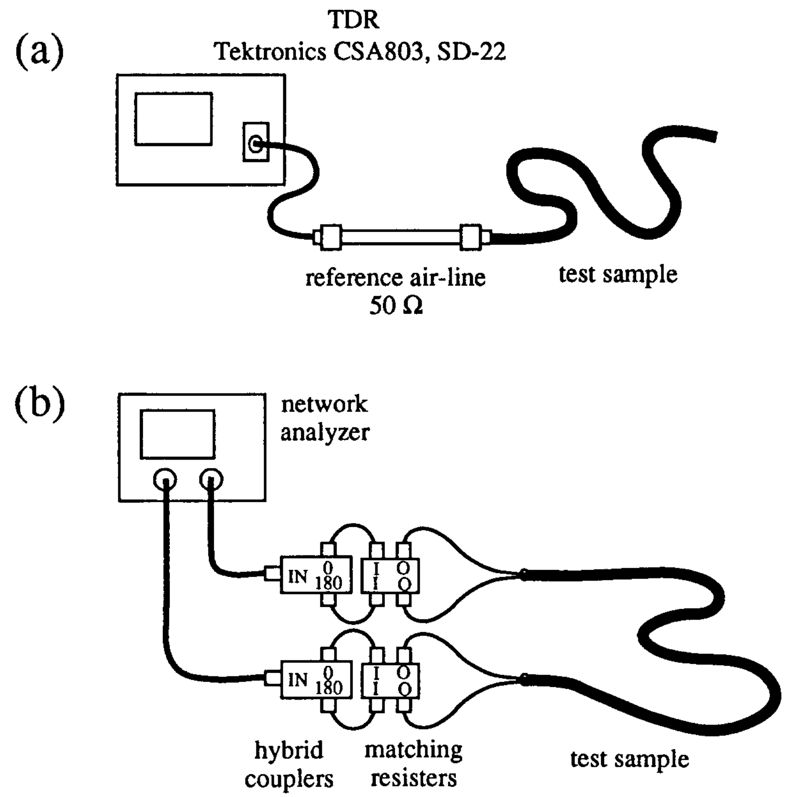

Fig. 2. The setup for the measurements performed at Junkosha: (a) the TDR method (TDR) and (b) for the network-analyzer method (NA).

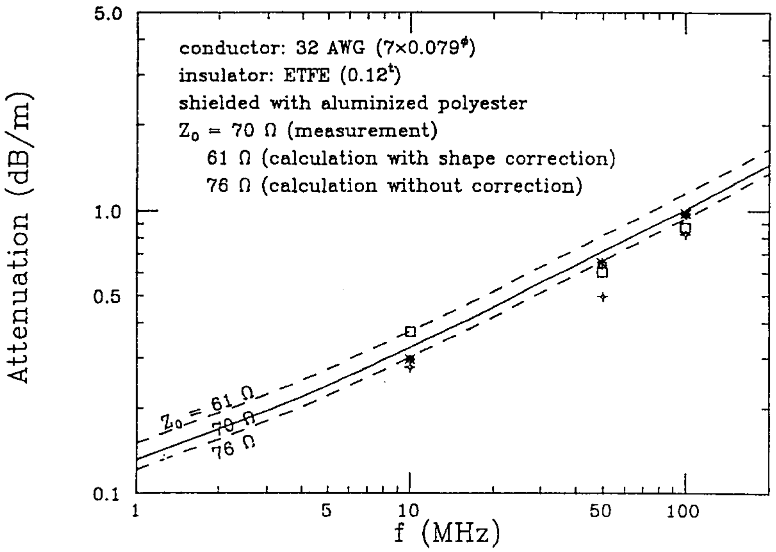

Fig. 3. The signal attenuation through the thin twisted-pair cable as a function of the signal frequency. The plots show the measurements by Junkosha, and the curves show the predictions for three impedance values: 61 Ω (race-track-shape shield), 70 Ω (measurement) and 76 Ω (round-shape shield).

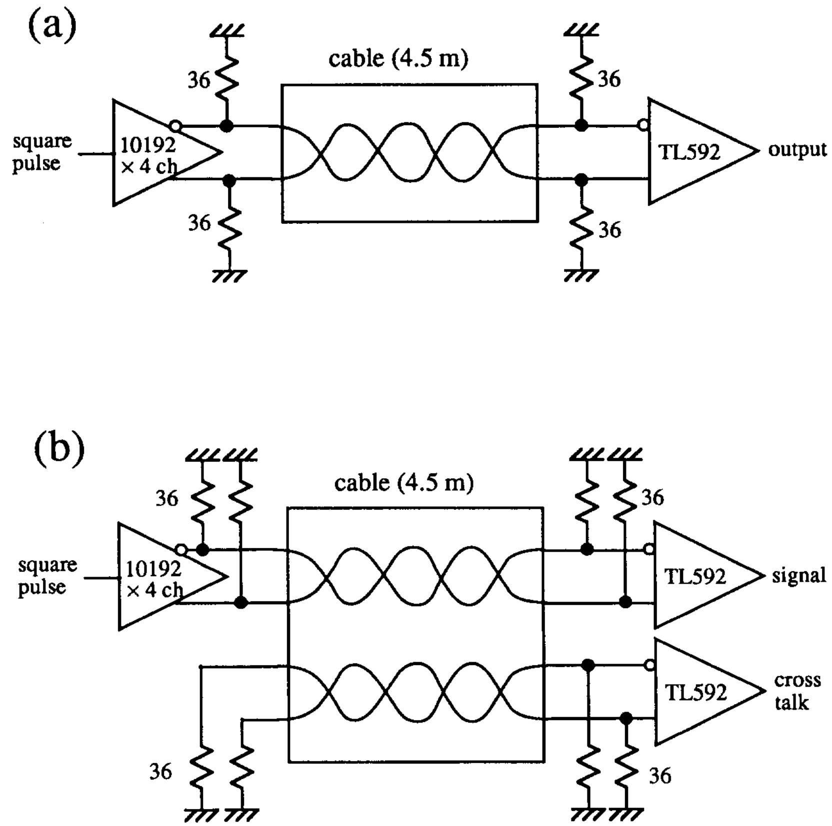

Fig. 4. Schematic diagrams to show the setup for the measurements of the thin twisted-pair cable performed at KEK: for the (a) attenuation and (b) cross talk measurements.

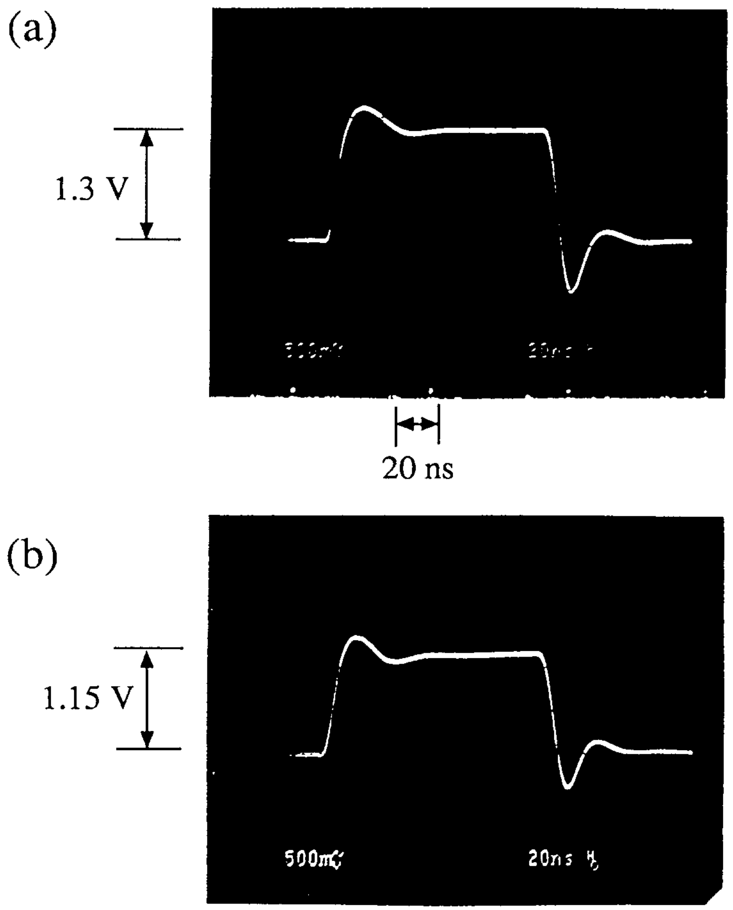

Fig. 5. The (a) input and (b) output signal shapes observed in the attenuation measurement of the thin twisted-pair cable performed at KEK.

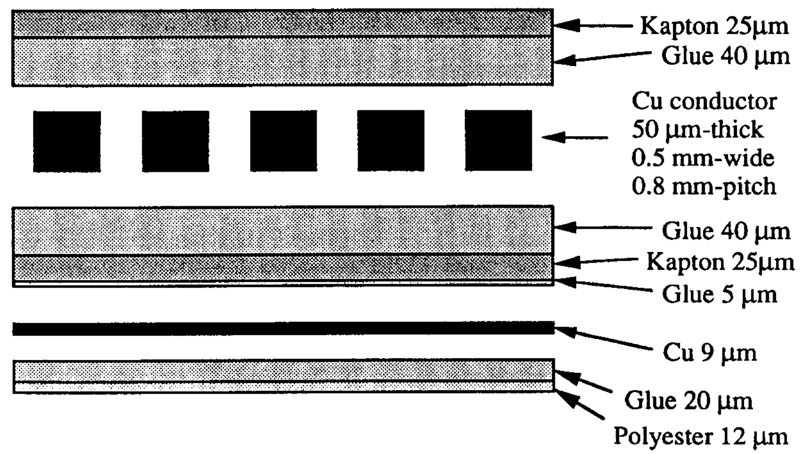

Fig. 6. A picture to show the components of the thin flat-cable fabricated by Hitachi Cable.

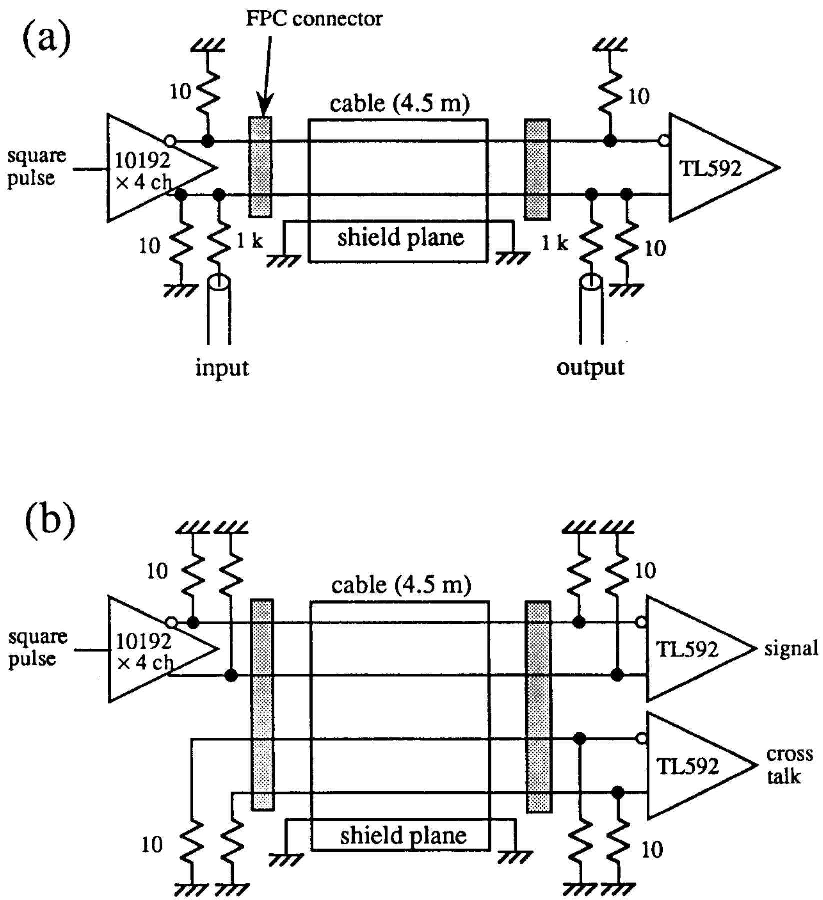

Fig. 7. Schematic diagrams to show the setup for the measurements of the thin flat-cable performed at KEK: for the (a) attenuation and (b) cross talk measurements.

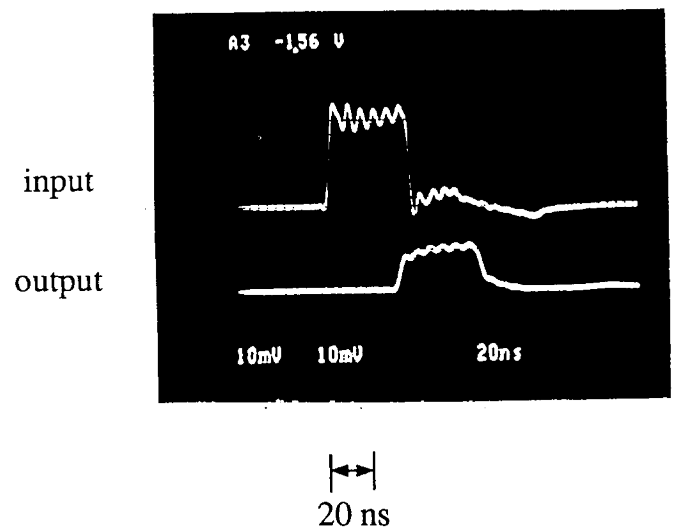

Fig. 8. The input and output signal shapes observed in the attenuation measurement of the thin flat-cable performed at KEK.

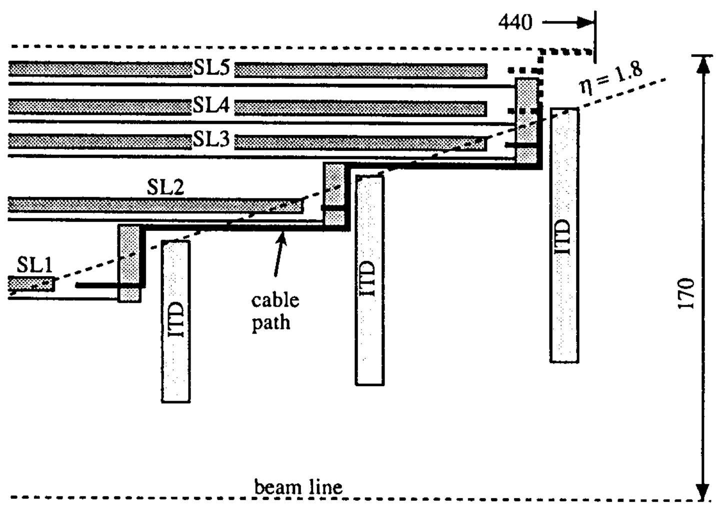

Fig. 9. The cable paths assumed in the estimation of the cable thickness in radiation length. The paths that may affect the tracking with ITD are drawn with solid lines, and the paths that would not affect it are drawn with dashed lines.

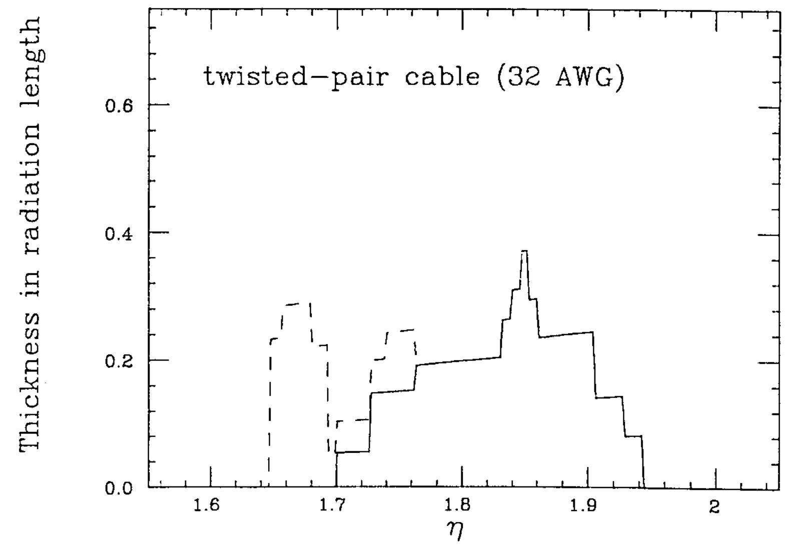

Fig. 10. The total thickness of the cables in the unit of radiation length, estimated by assuming a use of 61-pair bundles of the thin twisted-pair cables (32 AWG). The estimation is shown as a function of the pseudorapidity. The calculation was carried out according to the cable paths illustrated in Fig. 9. The solid curve shows the contribution of the paths drawn with solid lines in Fig. 9, and the dashed curve shows the total thickness including the paths drawn with dashed lines.