Development of Novel Optical Fiber Ribbon Assembled into Extremely High-Density Optical Fiber Cable

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Abstract
This paper proposes an extremely high-density optical fiber cable for access networks that uses novel optical fiber ribbon employing standard 250 μm diameter coated optical fibers.

We describe the requirements for these cables and investigate the structural design of the novel optical fiber ribbon taking the issues of cable downsizing and workability into consideration. On the basis of these requirements, we determined the geometry of the optical fiber ribbon and cable needed to achieve stable characteristics, sufficient long-term reliability and workability.

We confirmed that the novel optical fiber ribbon, which we call rollable optical fiber ribbon, had excellent mass splicing workability. Moreover, we manufactured a 200-fiber cable with a fiber density of 2.5 fibers/mm² and a cable diameter of 10 mm. We clarified that the transmission, mechanical characteristics and long-term reliability were sufficiently stable for the cable to be used in access networks for FTTH.

Keywords: Optical fiber cable; optical fiber ribbon; beinding loss insensitive fiber; FTTH.

1. Introduction
The growth in the demand for broadband services using optical access networks has led to a rapid increase in the number of FTTH subscribers. To provide these services in a timely way, we must construct optical fiber access networks swiftly, economically and effectively. If we wish to construct economical and efficient access networks, we need lightweight, high-density cables with a smaller cable diameter that can be installed easily.

Recently, several types of high-density optical fiber cable that assemble 250 or 200 μm diameter coated single optical fibers have been proposed [1-3]. The use of single optical fibers is well suited to high-density accommodation in cables. However, it restricts any possible increase in the fiber counts in cables because this would make fiber identification more difficult and reduce splicing efficiency. On the other hand, optical fiber ribbons are superior to single optical fibers as regards their capacity for mass splicing. However, the use of optical fiber ribbons in such high-density cables will lead to inflexibility. Moreover, a large strain will be applied to ribbon fibers in bent cables because some of the ribsions in the cables will be bent within their plane surfaces.

In this study, we propose an extremely high-density optical fiber cable that uses novel optical fiber ribbon. We design the structure of the cable and ribbon taking the two essential issues of cable downsizing and workability into consideration. Moreover, we manufactured extremely high-density optical fiber cable that uses the novel optical fiber ribbon, and examined its performance.

2. Requirements
Table 1 shows the requirements of optical fiber cables. The characteristics of these cables must remain stable in a variety of harsh environments. In addition, these cables must have a small diameter, be lightweight, highly reliable, and easy to install so that we can construct economical and efficient access networks. In this study, we developed aerial and rising optical fiber cable accommodating up to 200 fibers, which is enough to meet application region demands. Moreover, fiber joint workability (e.g. fiber identification and mass splicing) are also important when we construct access networks. In addition, to respond flexibly to user demands, we should employ aerial optical fiber cable to allow easy mid-span access after its initial installation.

Table 1. Requirements for optical fiber cable

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirements</th>
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<tbody>
<tr>
<td>General requirements</td>
<td></td>
</tr>
<tr>
<td>Mechanical characteristics</td>
<td>No loss change</td>
</tr>
<tr>
<td>Transmission characteristics</td>
<td>Low loss, stable</td>
</tr>
<tr>
<td>Temperature characteristics</td>
<td>Stable</td>
</tr>
<tr>
<td>Reliability</td>
<td>Sufficiently low failure rate</td>
</tr>
<tr>
<td>Practical requirements in this development</td>
<td></td>
</tr>
<tr>
<td>Application area</td>
<td></td>
</tr>
<tr>
<td>Aerial region</td>
<td></td>
</tr>
<tr>
<td>Rising region</td>
<td></td>
</tr>
<tr>
<td>Cable type</td>
<td></td>
</tr>
<tr>
<td>Self-supporting(SS) (w/ messenger wire)</td>
<td></td>
</tr>
<tr>
<td>Non self-supporting(N-SS) (w/o messenger wire)</td>
<td></td>
</tr>
<tr>
<td>Number of fibers</td>
<td>200(max.)</td>
</tr>
<tr>
<td>Workability</td>
<td>Optical fibers can be:</td>
</tr>
<tr>
<td>-easy identified and picked out</td>
<td></td>
</tr>
<tr>
<td>-mass spliced</td>
<td></td>
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</table>

First, we investigated the geometrical requirements for aerial cables to determine the messenger wire size based on the wind load conditions as shown in eqs. (1-3) [4].

\[ T_1 = E_A \left[ \alpha \left( t_c - t \right) + \frac{1}{24} \left( \frac{W \cdot S}{T} \right)^2 \right] - \frac{T}{E_A} \]

Here, \( W \) is cable weight, \( E_A \) is cable stiffness, \( \alpha \) is the equivalent linear expansion coefficient of the cable, \( t_c \) and \( t \) are temperatures (35 and -10 deg. C), \( S \) is the span length between telecommunication poles (60 m), and \( T \) and \( T_1 \) are the tensions on the cable calculated with (2) and (3).
Here, $d$ and $d_1$ are sag. Each cable weight is expressed by the following equations.

$$T = \frac{W \cdot S^2}{d} \quad (2)$$
$$T_1 = \frac{W_1 \cdot S^2}{d_1} \quad (3)$$

Here, $d$ and $d_1$ are sag. Each cable weight is expressed by the following equations.

$$W_1 = \sqrt{W^2 + W_0^2}$$
$$W = m \cdot g$$
$$W_0 = 100 \cdot g \cdot H \quad : \text{Class-A wind load condition}$$

Here, $H$ is the height of a cable with messenger wire.

Figure 1 shows the geometrical requirements for aerial cables. When the aerial cable weight and diameter fall within the hatched region in Fig. 1, we can use 4.2 mm (1.4 mm x 7) stranded steel wire as the messenger wire. This means that the weight and diameter of the cable are almost the same as that of conventional 40-fiber aerial cable [4], and it becomes easier to install it by using, for example, a manual installation method. Moreover, this cable can be installed into a small space of conduit in which thick cable such as metallic cable is already installed. This will allow us to increase the maximum fiber count in a conduit thus contributing to the effective use of underground facilities.

3. Cable design
3.1 Optical fiber cable and optical fiber ribbon structure

Figure 2(a) shows the configuration of the novel optical fiber ribbon that we call rollable optical fiber ribbon. This ribbon is composed of four coated optical fibers that are arranged linearly. The diameter of the coated optical fiber is conventional 250 µm. Two neighboring fibers are fixed together periodically in the longitudinal direction. This structure enables the optical fiber ribbon to be rolled up easily as shown in Fig. 2(b), and accommodated very tightly in cables. The ribbons can also be applied to mass fusion splicers and multi-fiber connectors (e.g. MT or MPO connectors [5, 6]) in the same way as conventional optical fiber ribbons.

Figure 3 shows the configuration of 200-fiber cable. This cable is composed of fifty 4-fiber rollable optical fiber ribbons, strength members, rip cords and a polyethylene sheath. The cable has ten units containing five rollable optical fiber ribbons, and each unit is stranded. The colored tapes are wound around each unit to enable them to be identified. The incorporated optical fiber is commercially available fiber categorized in ITU-T G.657.A1.

3.2 Structure optimization
3.2.1 Optical fiber ribbon. The adhesive dimensions $P$, $A$ and $B$ of the rollable fiber ribbon as shown in Fig. 4 may affect the fiber splicing workability. This is because the setup time for the fiber holder may be longer when $P$ and $B$ are longer. Therefore, we measured the splicing workability of rollable optical fiber ribbons with different adhesive dimensions using a conventional fiber holder. Figure 4 shows the relationship between splicing workability and adhesive dimensions. We found that the pitches $P$ and $B$ should be selected from the hatched regions in Fig. 4 to ensure splicing workability.
3.2.2 Stranding structure. In-service fibers in the same cable are handled during mid-span access operations. A large loss increase may result from unexpected fiber bending and twisting during these operations, and this may lead to bit error. This is closely related to the fiber handling workability, which depends on such cable structure characteristics as the stranded pitch. Therefore, we examined the fiber handling workability of the optical fiber cable with different stranding structure and stranding pitch characteristics. Figure 5 shows the results of a fiber handling workability evaluation. Here, \( P_{\text{unit}} \) is the stranding pitch of the units, \( P_{\text{ribbon}} \) is the stranding pitch of the ribbons and \( L_{\text{remove}} \) is length of sheath that is removed during a mid-span access operation. We found that the stranding pitch should be selected from the longer stranding pitch than filled circle in Fig. 5 to ensure the fiber handling workability of mid-span access.

4. Cable performance

4.1 Mechanical and transmission characteristics

We manufactured 24, 40, 60, 100 and 200-fiber cables. The manufactured cable diameter, weight and appearance are shown in Figs. 6 and 7, respectively. There is very little air space in the manufactured optical fiber cable and so extremely high density is achieved. We confirmed that the transmission and mechanical characteristics were stable as shown in Table 2.
4.2 Mechanical Reliability

When optical fiber cable is installed, optical fiber strain is induced by bending, and residual strain is caused by the cabling process and temperature changes. These strains are closely related to the cable and ribbon structure. Therefore, we investigated the fiber strain of the cable. Measured and estimated results are shown in Table 3. Here, $\epsilon_{b1}$, $\epsilon_{b2}$ and $\epsilon_r$ are measured by B-OTDR [7]. In addition, when the cable is bent, local strain that affects reliability is distributed in the longitudinal direction because of the ribbon structure. Therefore, we measured the maximum fiber strain caused by fiber bending $\epsilon_{b1}$ using an optical frequency domain reflectometry based setup, and analyzed the strain-induced frequency shifts of Rayleigh backscattering [8]. The measurement results are shown in Fig. 6. Moreover, we estimated the maximum strain caused by fiber bending, $\epsilon_{b2}$, which is approximated by eq. (4) [9, 10].

$$\epsilon_{eq} = \frac{0.83 \cdot d_{fiber}}{D} \sqrt{1 + 8 \cdot \pi^2 \cdot \left(\frac{R_{\text{scattered}}}{P_{\text{scattered}}}\right)^2 \frac{D}{2 \cdot P_{\text{scattered}}}}$$  \hspace{1cm} (4)

Here, $d_{fiber}$ is the optical fiber diameter (125 $\mu$m) and $D$ is the cable bending diameter. The calculation results are also shown in Fig. 6. We found that $\epsilon_{b1}$ and $\epsilon_{b2}$ depends on $D$, and $\epsilon_{b2}$ is less than 0.1% when $D$ is more than 600 mm, which is the fixed bending diameter of the cable currently in practical use.

Based on the results, we used eqs. (5) and (6) [11, 12] to calculate the failure rate of this cable, which is installed aerially.

$$F = \alpha N_p \gamma \left(\frac{e_{eq}}{e_r}\right)^{\beta} \frac{1}{2.7 \cdot 10^{-15} t_p}$$ \hspace{1cm} (5)

$$e_{eq} = \left[\int_{L_0}^{L_f} \left(\frac{1}{t_f} \int_{t_0}^{t_f} e^s dt\right)^{\beta} dl\right]^{1/\beta}$$ \hspace{1cm} (6)

Here $e_{eq}$ is the equivalent strain, $e$ is the fiber strain, $F$ is the failure rate of a fiber, $L_0$ is the fiber length, $N_p$ is the number of failures during a proof test, $e_r$ is the applied fiber strain during the proof test, $t_f$ is the time in use, $t_p$ is the proof test time, $n$ is the fatigue coefficient in use, $\eta_p$ is the fatigue coefficient during the proof test, and $\alpha$, $\beta$, and $\gamma$ are constants.

The calculated failure rate is $3.9 \times 10^{-6}$ fit/km/fiber, which is much less than the allowable failure rate of 0.01 fit/km/fiber. We confirmed that this cable has sufficient long-term reliability when in practical use.

### Table 3. Strain characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Strain %</th>
<th>Remark</th>
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</thead>
<tbody>
<tr>
<td>Residual after cabling, $\epsilon_{r}$</td>
<td>0.03</td>
<td>$L/L_0 = 1$, $t/t = 1$</td>
</tr>
<tr>
<td>Installation, $\epsilon_{i}$</td>
<td>0.03</td>
<td>$L/L_0 = 1$, $t/t = 1/10$</td>
</tr>
<tr>
<td>Residual after installation</td>
<td>Negligible</td>
<td>SS cable has excess cable length to messenger wire. N-SS cable is supported by cable bundling hanger [13].</td>
</tr>
<tr>
<td>Wind loading, $\epsilon_{w}$</td>
<td>0.03</td>
<td>$L/L_0 = 1$, $t/t = 1/10$</td>
</tr>
<tr>
<td>Temperature change, $\epsilon_c$</td>
<td>0.03</td>
<td>$L/L_0 = 1$, $t/t = 1/2$</td>
</tr>
<tr>
<td>Cable bending, $\epsilon_{b1}$</td>
<td>0.10</td>
<td>$L/L_0 = 1/10$, $t/t = 1$</td>
</tr>
<tr>
<td>Fiber bending, $\epsilon_{b2}$</td>
<td>0.035</td>
<td>$L/L_0 = 1/10$, $t/t = 1$</td>
</tr>
</tbody>
</table>

### Figure 8. Relationship between strain characteristics and cable bending diameter

5. Conclusions

This paper proposes an extremely high-density optical fiber cable for access networks that uses rollable optical fiber ribbon. The ribbon and cable structure is designed based on workability. We examined the cable characteristics, and found that the cable has sufficient long-term reliability and excellent workability for use in access networks for FTTH.

6. Acknowledgments

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7. References


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