Method for estimating loss over wide wavelength region of fiber cables installed in access networks

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Abstract: We propose a simple method for estimating the loss of installed cables to expand WDM access networks. Loss at arbitrary wavelengths can be very accurately predicted from the measured loss at a few wavelengths.

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1. Introduction

The FTTH network is now playing the leading role in delivering high-speed internet services. This has in turn encouraged the development of cost-effective WDM transmission systems, such as CWDM (G.694.2) and G-PON (G.984), which employ optical signals in different wavelength band. To introduce or upgrade these systems, it is essential that we design the optical loss over a wide wavelength range.

In general, we have constructed optical transmission systems based on a statistical design [1], which uses the mean values and standard deviations of the network elements. However, for systems with a large number of network elements, the margins may become unreasonably large. As a result, system performance would be severely limited. In addition, we have mainly employed 1.3 μm zero-dispersion single-mode fibers (SMF: G.652.A, B) as transmission lines in our access and user networks, and their loss characteristic changes greatly depending on the installation conditions, such as the splicing conditions and unexpected fiber bending. Therefore, if we can easily estimate the loss characteristics of installed fiber cables with high accuracy, this will help us to expand WDM access networks with a wide wavelength region. Several methods have been proposed for this purpose [2-4]. However, these methods require considerable modification if we are to apply them to installed cables [2], or we must measure the loss spectra of many installed fiber cables to construct a database for the estimation previously [3, 4].

In this paper, we propose a very simple method for estimating the loss of single-mode fiber cables installed in access and user networks. Without employing statistical techniques, this method enables us to predict loss values at any wavelength from the measured loss values at only three or four wavelengths. We employed this method for SMF cables already installed in user and access areas to confirm its high accuracy. We also propose its use for testing and maintaining cable lines with a multi-wavelength optical time domain reflectometer (OTDR).

2. Outline of proposed method

First, we constructed model equations that express the loss characteristics of installed fiber cables. The loss of optical fibers without any splicing or sharp bends is well fitted by the sum of the Rayleigh scattering, infrared absorption, OH impurity absorption, and structural imperfections in the fibers [5]. However, the loss characteristics of fiber cables are often affected by the installation conditions. Therefore, with installed cables, especially those in access and user area, we should consider the bending and splicing losses rather than the imperfection loss.

We employed eqs. (1) - (8) to express loss characteristics of installed fiber cables. In eq. (1), $\alpha_e(\lambda)$ indicates the total loss of the target cable. $\alpha_1(\lambda)$, $\alpha_2(\lambda)$, $\alpha_3(\lambda)$ and $\alpha_4(\lambda)$ are the Rayleigh scattering, splicing loss, sum of the infrared absorption and bending loss, and OH absorption, respectively. The Rayleigh scattering coeffient (R) of GeO_2-doped core fibers is well expressed by eqs. (2) and (3), where λ is the wavelength, R_{SiO2} is the Rayleigh scattering coefficient of pure-silica core fiber, and Δ is the relative refractive index difference [5, 6]. Since we mainly use MT-type connectors in our networks, we assume that the lateral offset is a dominant factor in $\alpha_2(\lambda)$. Then, we employ eqs. (4) - (6), where $2W(\lambda)$ is the mode-field diameter, k_1 is a constant, $V(\lambda)$ is the normalized frequency, and a and n_1 are the radius and refractive index of the core, respectively [7]. The sum of the infrared absorption and the bending loss is approximated by eq. (7), and the OH absorption is expressed by eq. (8), where k_2 is a constant and α_{OH} is a function given by the sum of the Gaussian and Lorentzian with different peak wavelengths and line widths [5, 8]. Since we usually know the kind of optical fibers in the target cable, we can obtain the values of R and $W(\lambda)$ in eq. (1) in advance by substituting their typical parameter values of Δ, a, and n_1 in eqs. (3)- (6). Therefore, we can easily modify this method to apply it to various kinds of single-mode fibers.

Figure 1 shows the principle of the method. The wavelength dependences of the loss factors vary considerably. If the loss values are given at three or four proper wavelengths that we call "pilot wavelength (λ_p)", the loss values at any wavelength can be analytically obtained by using eqs. (1) - (8), as follows. Since the E band is rarely utilized in

commercial WDM systems, we investigated the loss estimations over two different wavelength regions, namely, regions [I] and [II].
[I] Full band (O, E, S, C and L bands: 1260-1625nm)
Unfixed constants k_1, k_2, E and F in eq. (1) can be determined from the losses at four pilot wavelengths.
[II] Without E band (1260-1360nm, 1460-1625nm)
Unfixed constants k_1, E and F can be determined from the losses at three pilot wavelengths, assuming that k_2 is zero.

$$\alpha_e(\lambda)=\alpha_1(\lambda)+\alpha_2(\lambda)+\alpha_3(\lambda)+\alpha_4(\lambda) = R/\lambda^4 + k_1/W(\lambda)^2 + E\exp(-F/\lambda) + k_2\alpha_{OH}(\lambda) \qquad (1)$$

$$\alpha_1(\lambda) = R/\lambda^4 \quad (2), \qquad R=R_{SiO2}(1+0.62\Delta) \quad (3)$$

$$\alpha_2(\lambda) = k_1/W(\lambda)^2 \quad (4), \qquad W(\lambda)/a=0.65+1.619\,V(\lambda)^{-1.5}+2.879\,V(\lambda)^{-6} \quad (5)$$

$$V(\lambda)= 2\pi a\, n_1 (2\Delta)^{0.5}/\lambda \quad (6), \qquad \alpha_3(\lambda) = E\exp(-F/\lambda) \quad (7)$$

$$\alpha_4(\lambda) = k_2\alpha_{OH}(\lambda) \quad (8), \qquad S(\lambda)=\alpha_{2S}(\lambda)+\alpha_{3S}(\lambda)=k_{1S}/W(\lambda)^2+E_s\exp(-F_s/\lambda) \quad (9)$$

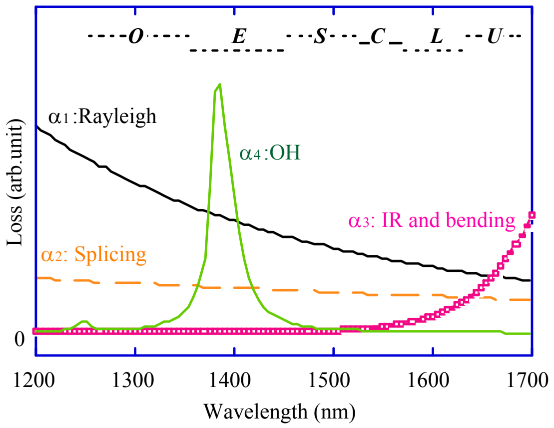

Fig. 1 Principle of method.

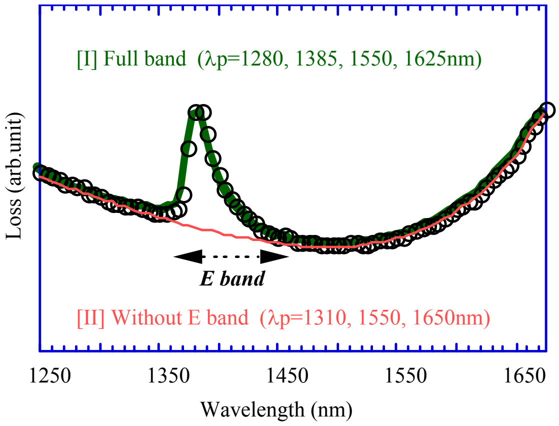

Fig.2 Examples of estimation.

3. Experimental results and discussions

To confirm the effectiveness of the method, we employed the loss spectra data of SMF cable lines already installed in user and access areas (N=62). These underground and aerial cables have quite a number of splicing points (approximately 1.5 points/km) because of the use of the fusion splices and MT-type connectors. The loss of each cable (α_m) was measured every 5 nm from 1200 to 1700 nm by using a test set-up composed of a white-light source, a monochromator and a power meter [9]. In the estimation, we assume that the values of R_{SiO2} and Δ are 0.8(dB/km/μm^4) and 0.35(%), respectively. As regards a and n_1, we employed typical values for SMF. The loss over the full band (α_e[I]) was estimated by using four pilot wavelengths of 1280, 1385, 1550 and 1625 nm. By contrast, the loss without the E band (α_e[II]) was estimated by using wavelengths of 1310, 1550 and 1650 nm.

Figure 2 shows examples of the estimation. The open circles are measured loss α_m, and the thick and thin lines express the estimated losses α_e[I] and α_e[II], respectively. The α_m value agrees well with α_e, which indicates that eq. (1) is appropriate for approximating the loss characteristics of installed fiber cables. Next we discuss the accuracy of this method. The relative difference ($D=(\alpha_m-\alpha_e)/\alpha_m$ (%)) was calculated for 62 different cable lines. Figures 3 and 4 show the results for [I] and [II], respectively. As expected, the deviation and absolute value of D also increase in the regions far from the pilot wavelengths. However, the D values fall within -9%～+8% for [I], and -10%～+6% for [II], in the 1260 to 1625 nm range. Therefore, as an example, we can estimate the loss at an arbitrary wavelength with an accuracy of better than 1 dB, when the actual loss of the cable is 10 dB.

As mentioned above, we can expect to obtain highly accurate loss estimations, simply by knowing the loss values at three or four wavelength. A multi-wavelength OTDR is a promising tool for measuring the loss at these pilot wavelengths. Since our cable line testing system is equipped with an OTDR with wavelengths of 1310, 1550 and 1650 nm [10], we can also utilize the method to clarify the cause of loss anomalies that appear in OTDR waveforms. Figure 5 shows a schematic representation of the analysis. By utilizing the waveforms, we can select an arbitrary section in the cable line. For example in Fig. 5, we can apply the method separately to sections (A) and (B) to analyze their loss characteristics. If anomalies, such as large bending or OH losses are found in either section, we have only to repair or replace the cable that corresponds to the anomalous section. When the loss anomaly is observed at the splicing point Q, there are two main possible causes, namely, the splicing loss ($\alpha_{2S}(\lambda)$) and the bending loss ($\alpha_{3S}(\lambda)$). Since the difference in the waveform level $S(\lambda)$ (dB) at point Q is given approximately by eq. (9), three constants k_{1S}, E_S and F_S can be decided analytically from the values of $S(\lambda)$ at three or four pilot wavelengths. In addition, it is shown theoretically that the splicing losses induced by both gap and tilt also decrease slightly with wavelength. By contrast, the bending loss increases rapidly with wavelength as shown in Fig. 1. Therefore, we can distinguish the bending loss from the splicing loss, and clarify a dominant cause of the anomaly at the splicing point.

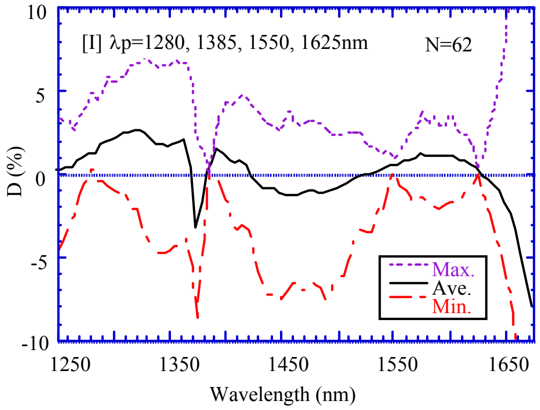

Fig. 3 Relative difference D([I]).

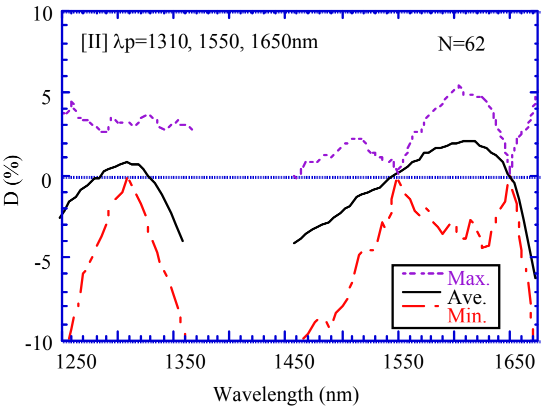

Fig. 4 Relative difference D([II]).

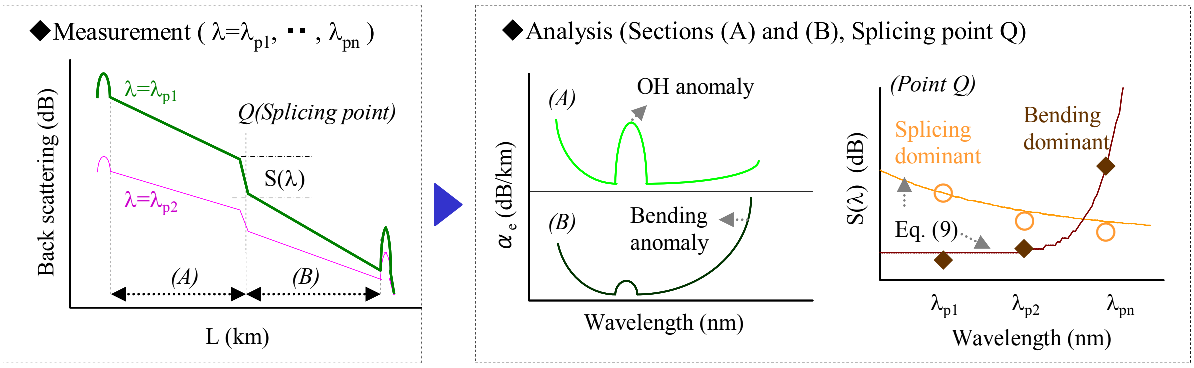

Fig. 5 Analysis of loss anomalies in OTDR waveform.

4. Conclusion

We proposed a simple method for estimating the loss of single-mode fiber cables installed in access and user networks. With this method, we can predict the loss values at any wavelength used in current WDM systems with high accuracy. We also proposed applying this method to the testing and maintenance of optical cable lines, and showed that the technique is useful for clarifying the cause of the loss anomalies observed in OTDR measurements.

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