Simple technique for measuring optical properties of randomly-coupled multi-core fiber using OTDR

Atsushi Nakamura1, a), Masaharu Ohashi2, Tomokazu Oda1, and Yusuke Koshikiya1

1 Access Network Service Systems Laboratories, NTT Corporation
1–7–1 Hanabatake, Tsukuba, Ibaraki 305–0805, Japan
2 Department of Technological Systems, Osaka Prefecture University College of Technology
26–12 Saiwai-cho, Neyagawa, Osaka 572–8572 Japan
a) atsushi.nakamura.wt@hco.ntt.co.jp

Abstract: We present a theoretical model and propose a technique based on this model for measuring the mode field diameter, relative-index difference, and chromatic dispersion along a randomly-coupled multi-core fiber using an optical time domain reflectometer. Experimental investigations demonstrate the feasibility of the technique.

Keywords: randomly-coupled multi-core fiber, mode field diameter, chromatic dispersion, optical time domain reflectometer

Classification: Optical Fiber for Communications

References

[1] T. Morioka, Y. Awaji, R. Ryf, P. Winzer, D. Richardson, and F. Poletti, “Enhancing optical communications with brand new fibers,” IEEE Commun. Mag., vol. 50, no. 2, pp. s31–s42, Feb. 2012. DOI: 10.1109/MCOM.2012.6146483
[2] D.J. Richardson, J.M. Fini, and L.E. Nelson, “Space-division multiplexing in optical fibres,” Nature Photonics, vol. 7, no. 5, pp. 354–362, April 2013. DOI: 10.1038/nphoton.2013.94
[3] T. Sakamoto, T. Mori, M. Wada, T. Yamamoto, F. Yamamoto, and K. Nakajima, “Fiber twisting- and bending-induced adiabatic/nonadiabatic super-mode transition in coupled multicore fiber,” J. Lightw. Technol., vol. 34, no. 4, pp. 1228–1237, Feb. 2016. DOI: 10.1109/JLT.2015.2502260
[4] T. Hayashi, Y. Tamura, T. Hasegawa, and T. Taru, “Record-low spatial mode dispersion and ultra-low loss coupled multi-core fiber for ultra-long-haul transmission,” J. Lightw. Technol., vol. 35, no. 3, pp. 450–457, Feb. 2017. DOI: 10.1109/JLT.2016.2614000
[5] K. Nakajima, M. Ohashi, and M. Tateda, “Chromatic dispersion distribution measurement along a single-mode optical fiber,” J. Lightw. Technol., vol. 15, no. 7, pp. 1095–1101, July 1997. DOI: 10.1109/50.596954
[6] A. Rossaro, M. Schiano, T. Tambosso, and D. D’Alessandro, “Spatially resolved chromatic dispersion measurement by a bidirectional OTDR technique,” IEEE J. Sel. Topics Quantum Electron., vol. 7, no. 3, pp. 475–483, May/June 2001. DOI: 10.1109/2944.962271
1 Introduction

Space division multiplexing (SDM) technologies using novel optical fibers are being intensively studied for expanding transmission capacity per fiber [1, 2]. Randomly-coupled multi-core fiber (RC-MCF) has recently attracted attention because of its high spatial channel density and unique optical properties, i.e., low differential group delay (DGD) and low mode-dependent loss (MDL) [3, 4]. In RC-MCFs, the fundamental properties of optical fibers, such as mode field diameter (MFD) and chromatic dispersion, are important as well as DGD and MDL. For the development and practical application of RC-MCFs, we require an easy-to-implement technique for measuring these optical properties.

Optical time domain reflectometer (OTDR) is an easy-to-use measurement tool since it can non-destructively characterize optical fibers from one end. It can obtain several important optical properties such as MFD and chromatic dispersion, while simultaneously measuring the loss distribution along the fiber [5, 6]. Previous studies demonstrated that the MFD, relative-index difference, and chromatic dispersion of uncoupled MCFs can be obtained using OTDR by considering the crosstalk between cores to be negligibly small [7, 8]. However, the idea of considering the crosstalk as zero cannot be applied to the measurements of RC-MCFs is usually too large to ignore. The applicability of the above OTDR based technique to the optical property measurements of RC-MCFs has not yet been fully clarified.

As a first step toward clarifying the applicability of the OTDR-based technique, a theoretical model and technique based on this model for measuring MFD, relative-index difference, and chromatic dispersion along a randomly-coupled two-core fiber (RC-2CF) by using OTDR for the first time are proposed. We experimentally demonstrate that this technique can successfully obtain these parameters.
2 Theoretical model

The basic principle of our technique is based on the bidirectional OTDR technique [7]. Figure 1 shows the measurement configuration of our technique. We use an RC-2CF that is the fiber under test (FUT) and two reference fibers (Ref #1 and Ref #2) with known properties. A given core at one end of the FUT is spliced to Ref #2. The other end of the given core is spliced to a short single-mode fiber so that we can measure the backscattered power from the opposite end of the given core. As the simplest example, we consider when the FUT has two homogeneous cores.

The backscattered power at distance $z$ measured from the left side in Fig. 1 can then be expressed as

$$P_{bs1}(z) = \begin{cases} 
P_0 \alpha_s(z) B(z) \exp(-2\alpha z) & (0 \leq z \leq L_0) \\
\frac{P_0}{2} \alpha_s(z) B(z) [1 + \exp(-4h(z - L_0))] \exp(-2\alpha z) & (L_0 < z \leq L_0 + L),
\end{cases}$$  

where $P_0$ is the input power, $\alpha_s$ is the scattering coefficient, and $B$ is the backscattering capture fraction. $\alpha$ is the attenuation coefficient. $h$ is the average power coupling coefficient of the FUT. $L_0$ and $L$ stand for the length of the reference fibers and the FUT, respectively. On the other hand, the backscattered power measured from the right side in Fig. 1 can be expressed as

$$P_{bs2}(z) = \begin{cases} 
\frac{P_1}{4} \alpha_s(z) B(z) [1 + \exp(-2hL)]^2 \exp[-2\alpha(L_0 + L - z)] & (0 \leq z \leq L_0) \\
\frac{P_1}{2} \alpha_s(z) B(z) [1 + \exp(-4h(L_0 + L - z))] \exp[-2\alpha(L_0 + L - z)] & (L_0 < z \leq L_0 + L),
\end{cases}$$

where $P_1$ is the input power. The imperfection contribution $I(z)$ can be expressed as

$$I(z) = 5 \log[P_{bs1}(z)] + 5 \log[P_{bs2}(z)]$$

$$= \begin{cases} 
10 \log[\alpha_s(z) B(z)] + H_1 + K & (0 \leq z \leq L_0) \\
10 \log[\alpha_s(z) B(z)] + H_2 + K & (L_0 < z \leq L_0 + L),
\end{cases}$$

where $K$ is a constant and given by

$$K = 10 \log \left( \frac{P_0 P_1}{4} \right) + 10 \log [\exp(-\alpha(L_0 + L))].$$

Here, $H_1$ and $H_2$ are the terms that depend on $h$ and expressed as

$$H_1 = 10 \log [1 + \exp(-2hL)].$$
and
\[ H_2 = 5 \log [1 + \exp(-4h(z - L_0))] + 5 \log [1 + \exp(-4h(L_0 + L - z))]. \] (6)

Since \( h \) is usually large in RC-MCFs, we can ignore the exponential terms including \( h \). In other words, \( H_1 \) and \( H_2 \) can be regarded as zero, and the imperfection contribution expressed by Eq. (3) can be considered independent of the crosstalk between the cores. Thus, we found that the OTDR technique can be used for measuring the optical properties of RC-2CFs as in the past since the imperfection contribution is independent of crosstalk. Note that the optical properties of MCFs with moderate power coupling coefficient cannot be obtained with the same method because the power coupling is too large to ignore, i.e., the imperfection contribution depends on the coupling coefficient.

Therefore, the MFD at a given position can be expressed in terms of the imperfection contributions and MFDs at two reference positions as [6]
\[ 2w(\lambda, z) = 2w(\lambda, z_1) \left( \frac{2w(\lambda, z_2) - I(z) - I(z_1)}{2w(\lambda, z_1) - I(z_2) - I(z_1)} \right), \] (7)
where \( w \) is the mode field radius (MFR) and \( \lambda \) is the wavelength. \( z_1 \) and \( z_2 \) are the positions where the MFD and relative-index difference in Ref #1 and Ref #2 are known, respectively.

Moreover, the relative-index difference \( \Delta \) can be expressed as [8]
\[ \Delta(z) = \frac{1}{k} \left( 1 + k\Delta(z_1) \right) \left( \frac{1 - k\Delta(z_2) - I(z_2) - I(z_1)}{1 + k\Delta(z_1) + I(z_1) - I(z_2)} \right) - 1, \] (8)
where \( k \) is the proportional constant of the Rayleigh scattering coefficient to the dopant concentration of GeO\textsubscript{2}-doped core fiber.

Chromatic dispersion \( D \) can be expressed as the sum of the material dispersion \( D_m \) and wavelength dispersion \( D_w \)
\[ D = D_m + D_w. \] (9)
The \( D_m \) and \( D_w \) can be expressed as [9]
\[ D_m = -\frac{\lambda^2 n}{c} \frac{d}{d\lambda}, \] (10)
\[ D_w = \frac{\lambda}{2\pi^2 cn} \frac{d}{d\lambda} \left( \frac{1}{w^2} \right), \] (11)
where \( c \) is the speed of light and \( n \) is the refractive index of the fiber core. The \( D_m \) can be obtained using the relative-index difference and Sellmeier’s relation [10]. The \( D_w \) can be estimated using the wavelength dependence of the MFR can be approximated as [5]
\[ w(\lambda, z) = g_1 + g_2 \lambda^{1.5} + g_3 \lambda^6, \] (12)
where \( g_1, g_2, \) and \( g_3 \) are the coefficients that can be determined from the measured MFR at three or more wavelengths. By substituting Eq. (12) into Eq. (11), \( D_w \) can
be expressed as
\[ D_w = \frac{\lambda}{2\pi^2cnw^2} \left\{ 1 - \frac{2\lambda}{w} \left[ \frac{3}{2} g_2\Delta^{0.5} + 6g_3\Delta^3 \right] \right\}. \] (13)

Therefore, we can obtain the chromatic dispersion using the MFR, relative-index difference, and Eqs. (9)–(13).

3 Experiments

We carried out experiments to demonstrate the proposed technique. We prepared an RC-2CF as the FUT, and two reference fibers (Ref #1 and Ref #2). The parameters of the FUT and reference fibers are listed in Table I. Note that the MFDs of the FUT were values calculated by taking the measured index profile into account, and the other parameters were measured values. The backscattered powers were measured with a commercially available OTDR (Yokogawa AQ7283K) from both sides of the fiber link. The pulse width was 200 ns, which corresponds to spatial resolution of 20 m, and the averaging number was 213.

| MFD at 1310 nm (μm) | Ref #1 | Ref #2 | FUT |
|---------------------|-------|-------|-----|
| 6.45                | 8.34  | 8.37* |
| 1550 nm             | 8.02  | 9.36  | 9.49* |
| 1625 nm             | 8.57  | 9.71  | 9.89* |
| Relative-index difference Δ (%) | 0.77  | 0.39  | 0.40 |
| Length (km)         | 10    | 0.5   | 2   |

* Calculated values by taking index profile into account.

Figure 2(a) shows the MFD distributions along the fiber link calculated using Eq. (7). The blue, red, and green lines represent the results for wavelengths of 1310, 1550, and 1625 nm, respectively. The MFDs obtained for each wavelength were in good agreement with the calculated values shown in Table I. The mismatches between the obtained and calculated values of a few percent are considered to be due to the difference between the actual and the ideally calculated field spreads.

Figure 2(b) shows the relative-index difference distribution along the fiber link estimated using Eq. (8). We used the \( k \) value of 0.62 [11]. The obtained relative-index difference of the FUT agreed well with that shown in Table I.

Figure 2(c) shows the chromatic dispersions along the fiber link. The blue, red, and green lines have the same meaning as those shown in Fig. 2(a). Furthermore, we obtained the chromatic dispersion as a function of wavelength using the experimental results at a distance of 11.5 km as an example. For comparison, we also measured the chromatic dispersion of the FUT using the time of flight (TOF) technique. Figure 2(d) shows the wavelength dependence of the chromatic dispersion. The solid line was obtained using Eqs. (9)–(13). The open circles were measured with the TOF technique. The obtained results were in good agreement with the calculated and measured results.

From these results, we experimentally confirmed that the proposed technique enables us to obtain MFD, relative-index difference, and chromatic dispersion of RC-2CFs. Further study is required to clarify measurement accuracy.
Fig. 2. Experimental results. (a) MFD distribution along fiber link. (b) Relative-index difference distribution. (c) Chromatic dispersion distribution. (d) Chromatic dispersion at distance of 11.5 km.

4 Conclusion

We presented a theoretical model for measuring MFD, relative-index difference, and chromatic dispersion along an RC-2CF using OTDR for the first time and proposed a technique based on this model. We experimentally clarified that the MFD, relative-index difference, and chromatic dispersion along an RC-2CF were successfully obtained with our proposed technique. It is planned to extend the model to obtain optical properties of RC-MCFs with more than two cores. Since this technique can be implemented by using a commercially available OTDR with simple numerical data processing, it will be useful for characterizing RC-MCFs.

Acknowledgments

We thank Dr. Nazuki Honda for her fruitful comments and constant encouragement.