Mode-dependent loss measurement of a two-mode fiber using a conventional OTDR

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Abstract: We propose a mode-dependent transmission-loss measurement technique for a two-mode fiber (TMF) using nonlinear least-squares regression of the data obtained by a conventional optical time-domain reflectometer (OTDR). The transmission loss of a 15-km-long TMF is successfully estimated by neglecting mode-coupling during propagation.

Keywords: mode-dependent loss, two-mode fiber, OTDR, least-squares method, mode filter

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References

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1 Introduction

Space-division multiplexing using multi-core fibers or few-mode fibers (FMFs) is a powerful and promising technology that can overcome the capacity limit of a single-mode fiber [1, 2, 3]. FMFs support more than one propagation mode. When mode-division multiplexed (MDM) transmission is used, there is a potential to increase the per-core transmission capacity. The mode-dependent loss (MDL) of optical components, including two-mode fiber (TMF), degrades transmission characteristics such as transmission distance and capacity [4, 5]. The MDL compensation technique is investigated to mitigate the MDL [6]. Measuring the MDL is also an important issue.

To measure the MDL in an FMF, it is essential to separate the propagating modes. The impulse response [7] and spatial decomposition methods [8] are utilized to separate propagating modes. Mode multiplexers or mode converters such as mode couplers or phase plates are another popular methods to separate propagating modes. Subsequently, the MDL is evaluated combining these methods with cutback or insertion methods. The optical time domain reflectometer (OTDR) method is often used to evaluate the transmission loss of conventional fibers, however, we could not find any reports of the MDL measurement using an OTDR.

In this study, we propose a simple MDL measurement technique for TMFs using a conventional OTDR and a mode filter. We derive a simple formula for the OTDR trace of TMFs by neglecting the mode-coupling during propagation. We perform nonlinear least-squares regression of the OTDR trace to obtain the transmission loss of each mode of the TMFs using this formula as a model function. We estimate the transmission loss of the fundamental mode and a high-order mode of a 15-km-long TMF.

2 Model function of TMF OTDR signal

When modeling an OTDR trace of the TMF measured by a conventional OTDR, we have to consider the transmission loss of each mode as well as the mode conversions. The mode conversion occurs during propagation, at an input, at an output, and at the scattering points of the TMF. By neglecting mode conversion within the propagating fiber and assuming that the backscattering coefficient is position independent, the approximated model function is derived as follows. Let $P_0$ be the launched power at the SMF, and assign the propagation loss of the $LP_{01}$ and $LP_{11}$ modes of the TMF to $a_{01}$ and $a_{11}$ dB/km, respectively.
The optical power of each mode at a fiber position \( z \) is given as follows:

\[
P_{01}(z) = P_0 A 10^{-\alpha_{01} z/10},
\]

\[
P_{11}(z) = P_0 B 10^{-\alpha_{11} z/10},
\]

where \( A \) and \( B \) are the mode-conversion coefficients at the splicing point between the \( LP_{01} \) mode of the SMF to the \( LP_{01} \) and to the \( LP_{11} \) mode of the TMF, respectively. Each mode is backscattered and recaptured as either the \( LP_{01} \) or the \( LP_{11} \) mode. The scattering coefficient is written as a \( 2 \times 2 \) matrix.

The backscattered light propagates back to the input end and experiences mode-conversion. Thus the received power is represented as follows:

\[
P'(z) = P_{01}(z)\sigma_{01}^{01} 10^{-\alpha_{01} z/10} A
\]

\[
+ P_{01}(z)\sigma_{01}^{11} 10^{-\alpha_{11} z/10} B
\]

\[
+ P_{11}(z)\sigma_{11}^{01} 10^{-\alpha_{01} z/10} A
\]

\[
+ P_{11}(z)\sigma_{11}^{11} 10^{-\alpha_{11} z/10} B.
\]

Here \( \sigma \)s are the backscatter recapture factors, where the subscripts of \( \sigma \) represent the input modes and superscripts represent the recaptured modes. Equation (2) is simplified as follows:

\[
P'(z) = A^2 P_0 10^{-2\alpha_{01} z/10}\sigma_{01}^{01}
\]

\[
+ AB P_0 10^{-\alpha_{01} z/10}\sigma_{01}^{01} + \sigma_{11}^{01}]
\]

\[
+ B^2 P_0 10^{-2\alpha_{11} z/10}\sigma_{11}^{11}.
\]

Equation (3) contains a three-component exponential decay function with eight parameters. Here we are interested in the decay constants of the exponential terms, and therefore, we group the amplitude parameters of each term so that

\[
P'(z) = K_0 10^{-2\alpha_{01} z/10} + K_1 10^{-\alpha_{01} z/10} + K_2 10^{-2\alpha_{11} z/10},
\]

which reduces the number of parameters to five. In principle, we can determine both \( \alpha_{01} \) and \( \alpha_{11} \) using nonlinear least-squares regression. The nonlinear least-squares regression of a multi-exponential function tends to converge to an inappropriate value when the exponential terms have similar decay constants. This usually happens in TMF because the TMF must propagate two modes over long distances. We use a mode filter, which gives an intentional MDL, just after the splicing point to reduce the high-order mode. If the mode filter completely eliminates the \( LP_{11} \) mode, the mode conversion coefficient \( B \) becomes 0. In this condition, Eq. (4) becomes

\[
P'(z) = K_0 10^{-2\alpha_{01} z/10},
\]

which is the same equation as that of the conventional OTDR signal. Thus the transmission loss \( \alpha_{01} \) of the \( LP_{01} \) mode is obtained either conventionally or by curve fitting. Similarly if the mode filter completely eliminates the \( LP_{01} \) mode, the transmission loss \( \alpha_{11} \) of the \( LP_{11} \) mode is conventionally obtained. Mode multiplexers may be used for this purpose however, it is difficult to completely eliminate the fundamental mode when using mode multiplexers over a wide wavelength range. Once \( \alpha_{01} \) is determined, Eq. (4) becomes a two-component exponential decay function as follows:
\[ P'(z) = K_0 f(2z) + K_1 f(z) 10^{-a_{11} z^2/10} + K_2 10^{-2a_{11} z^2/10}, \]

where \( f(z) = 10^{-a_{01} z/10} \). The transmission loss \( a_{11} \) of the \( LP_{11} \) mode is obtained by a nonlinear least-squares regression of the OTDR trace using this equation as a model function.

### 3 Measurement

Fig. 1 shows a schematic of the experimental setup. We used a non-modified Agilent E6003A Mini-OTDR. The wavelength was 1550 nm, the averaging time was 180 s, the pulse width was 100 ns, and the measurement range was 20 km. We prepared a 15-km-long TMF with a large MDL. The SMF and TMF were spliced in order to maintain the launch condition. A transversal offset was intentionally introduced at the splicing point.

![Schematic of measurement setup.](image)

To apply the proposed method to an arbitrary fiber, we need to determine the bending diameter and number of winding turns of the mode filter that eliminates the high-order modes without affecting the fundamental mode power. The optical power change due to the fiber bend was monitored by an OTDR signal. We chose the bending diameter for which the received optical power decreases. Subsequently, we checked whether the power converges to a certain value by increasing the number of winding turns. If the power does not converge, it indicates that the fundamental mode is attenuated by the fiber bend, i.e., the high-order modes are not excited in the TMF. Fig. 2 shows the backscattered power as a function of the number of winding turns of the fiber when the bending diameter was 16 mm. The red circles represent the sum of the power in the range 1.0–1.1 km obtained by the OTDR signal. The obtained backscattered power becomes nearly constant when more than 15 winding turns are used. The broken line is the least-squares fit of the measured value to a single exponential plus a constant. Assuming that the mode filter did not affect the \( LP_{01} \) mode, the constant power indicates the power of the \( LP_{01} \) mode and the rest is the power of the \( LP_{11} \) mode. The obtained mode-reduction ratio of the mode filter was \( \sim 1 \) dB/turn. The power ratio of the \( LP_{11} \) mode to the \( LP_{01} \) mode in Fig. 2 for no fiber windings was approximately \( -6 \) dB. Note that this ratio is not a mode excitation ratio in the TMF. The mode excitation ratio \( LP_{01}:LP_{11} \) at the input end of the TMF that we measured for reference by the bending method was 3:1 (\( -4.8 \) dB). In this case, the ratio of the received \( LP_{11} \) mode power to that of \( LP_{01} \) after 15 winding turns of the TMF was \( \sim 1 \)% of the measured power.

We calculated the transmission loss of the \( LP_{01} \) mode of the TMF from the OTDR trace in the range 1–14 km with a mode filter of 22.5 winding turns. The
Transmission loss of the \( LP_{11} \) mode was calculated using nonlinear least-squares regression of the OTDR trace without a mode filter and the transmission loss of the \( LP_{01} \) mode obtained above. Nonlinear least-squares regression was performed using the Levenberg-Marquardt algorithm [9]. The obtained average transmission losses of the \( LP_{01} \) and \( LP_{11} \) modes of the TMF were 0.2774 dB/km and 0.5913 dB/km, respectively.

Fig. 3 shows the fitted curve overlaid on the obtained OTDR trace with and without the mode filter of 22.5 winding turns. The solid lines indicate the measured OTDR traces and the dashed lines indicate the fitted curves. The latter are nearly identical to the measured data, and therefore, the obtained fitted values are acceptable.

To test the reproducibility of our method, we performed the measurement four times. We used 15 winding turns and the TMF was unwound and rewound for each measurement while the splicing point was left unchanged. The average and standard deviation of the estimated transmission loss in the four measurements for the \( LP_{01} \) and \( LP_{11} \) modes were 0.2772 ± 0.00033 dB/km and 0.494 ± 0.010 dB/km, respectively. Assuming that the transmission loss obtained by the OTDR trace with a mode filter of 22.5 winding turns is close to the appropriate value, the estimation error of the \( LP_{11} \) mode obtained with a mode filter of 15 winding turns was 0.05 dB/km. The fluctuation of each measurement was smaller than the estimation error caused by the residual high-order mode power.

In this method, it is important to use a mode filter of high mode extinction ratio. An insufficient extinction ratio of the mode filter causes the \( LP_{11} \) mode to leak through the mode filter. The power of the leaked \( LP_{11} \) mode was regarded as a part...
of the power of the $LP_{01}$ mode. In other words, the power of the $LP_{11}$ mode was under-estimated throughout the fiber position. In general, $\alpha_{01} < \alpha_{11}$, and thus, the transmission loss of the $LP_{11}$ mode was over-estimated.

4 Conclusion

We have proposed an MDL measurement technique for a TMF using nonlinear least-squares regression of the data obtained by a conventional OTDR. We have successfully measured the transmission losses of the $LP_{01}$ and $LP_{11}$ mode of a 15-km-long TMF.

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