Direct technique for measuring chromatic dispersion of high-order mode in a few-mode fiber

Ryuki Miyazaki\textsuperscript{1a), Masaharu Ohashi\textsuperscript{1b), Hirokazu Kubota\textsuperscript{1}}, Yuji miyoshi\textsuperscript{1}, Nori Shibata\textsuperscript{2}, Ryo Maruyama\textsuperscript{1, 3}, and Nobuo Kuwaki\textsuperscript{4}

\textsuperscript{1}Graduate School of Engineering, Osaka Prefecture University
Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
\textsuperscript{2}College of Engineering, Nihon University
Koriyama, Fukushima, 963-8642 Japan
\textsuperscript{3}Optical Fiber Division, Fujikura Ltd.
1440, Mutsuzaki, Sakura, Chiba, 285-8550, Japan
\textsuperscript{4}Corporate R&D Unit, Fujikura Ltd.
Koto, Tokyo, 135-8512, Japan
a) swb01166@edu.osakafu-u.ac.jp, b) ohashi@eis.osakafu-u.ac.jp

Abstract:
We propose an interferometric technique for directly measuring the chromatic dispersion of the high-order mode in a few-mode fiber (FMF) by using a mode converter (MC). We successfully estimate the chromatic dispersion of the LP\textsubscript{11} mode in the test fiber by using the proposed technique.

Keywords: interferometer, chromatic dispersion, few-mode fiber, mode converter

Classification: Fiber-Optic Transmission for Communications

References

[1] J. Sakaguchi, W. Klaus, J. M. D. Mendinueta, B. J. Puttnam, R. S. Luis, Y. Awaji, N. Wada, T. Hayashi, T. Nakanishi, T. Watanabe, Y. Kokubun, T. Takahata, and T. Kobayashi, “Large spatial channel (36-core3 mode) heterogeneous few-mode multicore fiber,” J. Lightwave Technol., vol. 34, pp. 93-103, 2016. DOI:10.1109/JLT.2015.2481086

[2] T. Hayashi, T. Nagashima, K. Yonezawa, Y. Wakayama, D. Soma, K. Igarashi, T. Tsuritani, and T. Sasaki, “6-mode 19-core fiber for weakly-coupled mode-multiplexed transmission over uncoupled cores,” OFC 2016, W1F.4, Anaheim, 2016.

[3] T. J. Ahn, Y. Jung, K. Oh, and D. Y. Kim, “Chromatic dispersion measurement for a few-mode fiber using optical frequency-domain reflectometer,” CLEO/QELS 2006, JTuD69, Long Beach, 2006.
[4] P. Hamel, Y. Jaouën, R. Gabet, and S. Ramachandran, “Optical low-coherence reflectometry for complete chromatic dispersion characterization of few-mode fibers,” Opt. Lett., vol. 32, pp.1029-1031, 2007. DOI:10.1364/OL.32.001029

[5] N. Shibata, M. Ohashi, R. Maruyama, and N. Kuwaki, “Measurements of differential group delay and chromatic dispersion for LP01 and LP11 modes of few-mode fibers with depressed claddings,” Opt. Rev., vol. 22, pp. 65-70, 2015. DOI:10.1007/s10043-015-0056-y

[6] R. Miyazaki, M. Ohashi, H. Kubota, Y. Miyoshi, and N. Shibata, “Chromatic dispersion measurement of the high order mode in a few-mode fiber using an interferometric technique and a mode converter,” Proc. of the 22nd Opto-Electronics and Communications Conference, Singapore, P3-067, Aug. 2017.

1 Introduction

Mode division multiplexing (MDM) has been developed intensively by using few-mode fibers (FMF) to expand their transmission capacity [1, 2]. It is known that differential group delay (DGD) between modes, their chromatic dispersions, and optical loss are important parameters when designing MDM systems.

Many reports have been published on techniques for measuring the dispersion characteristics of FMF, including optical frequency-domain reflectometry [3], phase-sensitive optical low-coherence reflectometry [4], and modal interferometer method [5]. According to [5], the chromatic dispersion in the LP11 mode can be estimated by measuring the differential group delay between the LP01 and the LP11 modes in conjunction with the group delay time in the LP01 mode.

In this paper, we propose an interferometric technique for directly measuring the chromatic dispersion of the high-order mode in an FMF by using a mode converter (MC). We successfully estimate chromatic dispersion of the LP11 mode in the test fiber by using this technique. This technique can be applied to chromatic dispersion measurements of high-order modes in FMFs by using a suitable MC, if the mode coupling between modes is ignored.

2 Measurement Principle

Fig. 1 shows a diagram of an interferometer for measuring group delay /transit time difference between two optical paths in an optical fiber and a wave propagating in the air [6]. Before the polarizer, P1, an MC is inserted to convert the LP01 mode to the high-order mode. The interferometer facilitates measurement of the wavelength dependence of DGD and transit time delay of the high-order mode.

The beam of high-order mode emitted from the MC is divided into two beams by using a half mirror HM1. One of these beams is launched into the test FMF, while the other is propagated through air. The direction of the beam in air is changed by the mirrors M1 and M2, and it is superposed on the beam emitted from the FMF by another half mirror HM2. The moving mirror M3 is adjusted so that the two optical paths can be made identical, which corresponds to $d=0$, where $2d$ is the group time delay of the path difference between the two optical paths. The polarizer P2 is adjusted to achieve the maximum dip in the optical spectrum analyzer (OSA) trace. Here, DGD is defined as $\Delta \tau = \tau_h - \tau_{air}$, where $\tau_h$ and $\tau_{air}$ are the group time delays of the high-order mode and the wave propagating in the
air, respectively.

The DGD $\Delta \tau$ between the two optical paths is expressed as follows [5]:

$$\Delta \tau = \tau_h - \tau_{\text{air}} = -\frac{\lambda^2}{cL\Delta \lambda} + 2d / (cL)$$

(1)

where $c$ is the velocity of light in free space, $L$ is the fiber length, $\lambda$ is the center wavelength of the adjacent minima, and $\Delta \lambda$ is the difference between the wavelengths of the adjacent minima in the trace.

Therefore, the chromatic dispersion $D_h$ of the high-order mode can be obtained by differentiating $\tau_h$ with respect to the wavelength as follows:

$$D_h = d\tau_h / d\lambda$$

(2)

$D_h$ can be estimated experimentally by differentiating the wavelength dependence, $\tau_h - \tau_{\text{air}}$, with respect to wavelength, as shown in (2). Chromatic dispersion in the LP$_{01}$ mode can be estimated experimentally in the same way by launching the LP$_{01}$ mode into the test FMF through MC and P$_1$.

3 Experimental Results

We used a super-luminescent diode (SLD) operating at a center wavelength of 1540 nm as the light source in our experiments. We prepared the test FMF with chromatic dispersion of LP$_{11}$ mode of 17.3 ps/nm/km at 1.55 $\mu$m, which was calculated taking the index profile into account. The MC (Optoquest Co., Ltd.) was used to covert the LP$_{01}$ mode to the LP$_{11}$ mode.

Fig. 2 shows the interference trace between the LP$_{11}$ mode in the FMF and the wave in air obtained using 0.78 m long FMF. The interference fringe was clearly visible in the trace. We observed the field pattern of the light wave emitted from the test FMFs by using an infrared vidicon camera (Hamamatsu Photonics), as shown in the inset of Fig. 2. The field pattern coincides with that of the LP$_{11}$ mode. We confirmed that the spectrum shown in Fig. 2 was the interference between the LP$_{11}$ mode in the FMF and the wave traveling in air.
The transit time delay difference $\tau_{11} - \tau_{\text{air}}$ can be obtained from Fig. 2 by using Eq. (1). Fig. 3(a) shows the DGD properties of the test fiber. The open circles represent the experimental results obtained using the test fiber. The solid line shows the best fit of the experimental results by using a quadratic function. The chromatic dispersion of the LP$_{11}$ mode can be computed using Eq. (2) and Fig. 3(a). Therefore, the chromatic dispersion can be estimated by differentiating the fitting curve, shown in Fig. 3(a), with respect to wavelength. Fig. 3(b) shows the chromatic dispersion plotted as a function of wavelength.

Fig. 2. OSA trace obtained for transit time delay difference $\tau_{11} - \tau_{\text{air}}$

Fig. 3. (a) DGD as a function of wavelength. (b) Chromatic dispersion of the LP$_{11}$ mode in the test FMF.
The red line shows the chromatic dispersion of the LP_{11} mode measured using the technique proposed herein. The blue line shows the calculated chromatic dispersion plotted as a function of wavelength, which was calculated taking the index profile into account. The chromatic dispersion of the test fiber differs slightly from the calculated value.

Discrepancies between the two sets of chromatic dispersion values obtained at 1.55 μm are shown in Fig. 3(b). The intensity distribution shown in Fig. 3(a) suggests that these discrepancies arise from ambiguity with respect to the determination of the positions of interference signal peaks.

As a result, we confirmed that the proposed technique can be used directly to measure the chromatic dispersion of the high-order mode, as well as the fundamental mode, in FMFs given an MC that can convert the LP_{01} mode to the desired mode.

4 Conclusion

We proposed an interferometric technique for measuring the chromatic dispersion of the high-order mode of a FMF by using an MC. The chromatic dispersion of the LP_{11} mode in the test FMF was successfully measured using this technique. It was confirmed that the proposed technique can be applied to direct measurement of the chromatic dispersion of the high-order mode in FMFs, given mode converters that can convert the LP_{01} mode to the desired mode.

Acknowledgment

This research is partially supported by the National Institute of Information and Communications Technology (NICT), Japan, under “Research on Innovative Optical Fiber Technology.”