Two-dimensional Linear Optical Sampling for Ultrafast Spatial Mode Analysis

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Abstract Two-dimensional linear optical sampling is presented for observing ultrafast spatiotemporal complex signals. By directly observing complex cross-sectional images, the technique is useful for spatial modes of multimode/multicore fibres. The intramodal delay differences in step-index and graded-index fibres are analysed with a ps-level time resolution.

Introduction

To overcome the nonlinear Shannon limit which has become apparent in single-mode fibre transmission, space-division multiplexing (SDM) technology has been intensively investigated [1,2], as well as the characterization techniques for SDM transmission systems [3-7]. One of the promising optical fibres for SDM is a few-mode fibre (FMF) [8-10]. In addition to the fundamental mode (LP_{01} mode), higher-order modes (LP_{11}, LP_{21}, etc) are multiplexed into a single core to expand capacity. Every linear polarization (LP) mode consists of the true eigenmodes [11], which propagate with approximately the same propagation constants. The impulse response of FMF involves both the intermodal and intramodal dispersions [12], while the former is generally much larger than the latter. For characterizing the spatial mode dispersion (SMD), it is beneficial to directly observe the spatiotemporal complex profile of signals which emerges from FMFs. Such a "high-speed complex amplitude camera" can be realized by combining coherent detection with a photodetector array (PDA) [13]. However, the implementation of the high-speed PDAs requires advanced high frequency techniques. Although complex spatiotemporal measurement of ultrafast pulses was presented based on wavelength-multiplexed holography [14], the demonstrated signal lengths and fibre lengths were very limited.

Linear optical sampling (LOS) [15,16] is a sampling technique that detects the instantaneous amplitude of a signal light by interfering a short pulse with the optical signal. The required response speed of the photodetector is only about the repetition frequency of the sampling pulses, enabling ultrafast measurements using a slow photodetector. Recently, we presented the two-dimensional linear optical sampling (2D-LOS) [17], in which, the mode field of the multimode fibre output was projected onto 2×2 slow photodetector arrays (PDAs), and its ultrafast dynamics was observed by the LOS scheme. It was also shown that the modal decomposition of the observed field profile into each eigenmode was successfully performed.

In this paper, we demonstrate the 2D-LOS to observe the impulse responses a step-index 2-LP-mode fibre (SI2MF) and a graded-index 2-LP-mode fibre (GI2MF) with a length of approximately 1-km. In particular, pulses excited in LP_{11} mode were observed, and the pulse broadening due to the intramode delay differences was compared between the two types of fibres. Thanks to the modal decomposition function, it is observed that the arrival time of each eigenmode randomly varies, suggesting that strong mode mixing is occurring inside the LP_{11} mode group.

Eigenmode analysis and Experiment setup

As well known, cylindrical optical fibres support the eigenmodes called transverse electric (TE), transverse magnetic (TM), and hybrid (HE, EH) modes. Among these true

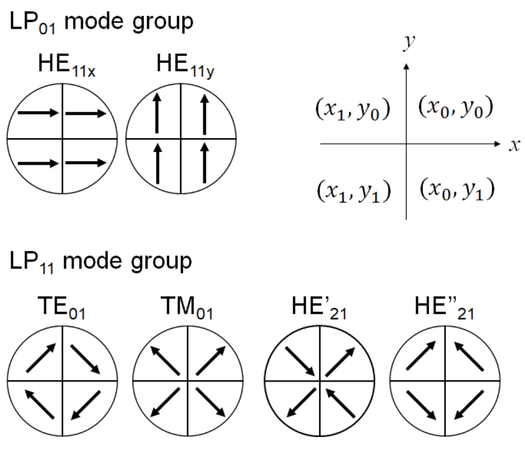

Fig. 1: Field vectors of the eigenmodes in a 2-LP-mode fibre at four points in Cartesian coordinates.

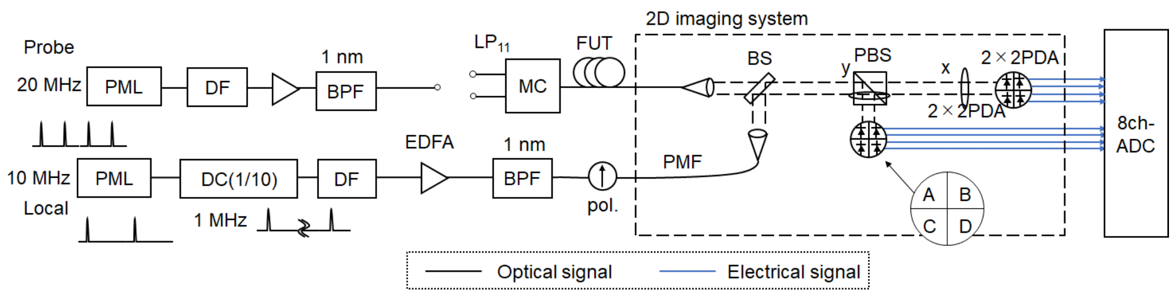

Fig. 2 Experimental setup. PML: passive mode-locked laser. DF: dispersive fibre. DC: down-converter. pol.: polarizer. BPF: band pass filter. pc: polarization controller. MC: mode combiner. FUT: fibre under test. BS: beam splitter. PBS: polarization beam splitter. 2D-PDA: 2-dimensional photodetector array. 8-ch ADC: 8-channel analog-to-digital convertor.

eigenmodes, the group of modes whose propagation constants are almost equal constitute the linear polarization mode (LP mode). For example, the LP_{01} mode, which is the fundamental mode, is the HE_{11} mode, and the LP_{11} mode, which is one of the higher-order modes, is expressed as a linear combination of two of the TM_{01}, TE_{01}, HE'_{21}, and HE''_{21} modes. The field vectors sampled at four centrally symmetric spatial points for the eigenmodes comprising the two LP modes are shown in Fig. 1. By correlating the arbitrary received mode field profile $\vec{E}$ with that of each eigenmode $\vec{\varphi}$, the modal decomposition can be accomplished. The complex amplitude $c(t)$ of the eigenmode involved in the received field can be obtained as

$$c(t) = \sum_{i,j} \vec{E}(x_i, y_j, t)\vec{\varphi}^*(x_i, y_j). \qquad (1)$$

Fig. 2 shows the experimental setup of the 2D-LOS. The probe pulse was provided by a passive mode-locked laser (PML) with a repetition rate of 20 MHz. The pulses supplied by PML are almost Fourier transform-limited pulses. A dispersive fibre (DF) was then used to give a dispersion of -50.4 ps/nm. After being amplified by an Er-doped fibre amplifier (EDFA), a spectral width of ~1 nm was filtered with a Gaussian-like band-pass filter (BPF). The probe pulse was introduced to the mode combiner attached to the fibre under test (FUT), to excite the LP_{11} mode of the FUT. The probe pulse which emerged from the fibre was input to the 2-D imaging system. We prepared two types of FUTs: step-index 2-mode fibre (SI2MF) and graded-index 2-mode fibre (GI2MF). The length of both the FUTs was approximately 1 km.

The local pulse is provided by a pulse train from another PML with a repetition rate of 10 MHz. This sampling pulse rate was downconverted to 1 MHz, by using an acousto-optic modulator of over 50-dB extinction ratio, which extracted every tenth pulse. The reason for this down-conversion is that the bandwidth of the receiver including the 2D-PDA was only a few MHz, and the sampling rate must be smaller than the bandwidth. A DF (-40.4 ps/nm) was used to add dispersion to the input pulse to reduce the peak power, before being amplified by an EDFA. The sampling pulse was filtered by an optical bandpass filter with the same centre wavelength and bandwidth as those used for the probe pulse. This spectral overlap between the probe and local pulses is essential for the LOS. Then, the sampling pulse was input to the imaging system with 45° linear polarization. The effective sampling interval was adjusted to be ~1 ps, by controlling the repetition rate of the two independent PMLs.

A beam splitter (BS) and a polarizing beam splitter (PBS) are built into the imaging system. The probe pulse and local pulse were combined by BS and separated into x and y polarizations by PBS. For later descriptions, we label each photodetector of the 2D-PDA as A-D, as shown in Fig. 2. The photocurrent generated by a total of eight PDs was converted to a voltage by a 1kΩ resistor, and the voltage was collected by a 12-bit 8-channel analog-to-digital converter (8ch ADC). The data was collected with an external clock synchronizing to the local pulse.

Only the In-Phase component was acquired in the measurement. Later in the numerical analysis, the Hilbert transform is performed and the corresponding complex signal was generated. By using Eq. 1 with the aquired voltages at each photodetactors, the modal decomposition was performed.

Results

Fig. 3 shows the interference signals obtained in the SI2MF and GI2MF, respectively, when the probe pulse was input to FUTs from the LP_{11} port of the mode combiner. The four coler plots correspond to PDs A-D, respectively. In the top diagrams, two pulses were observed in each of SI2MF and GI2MF. These two pulses are believed to be in the LP_{01} and LP_{11} modes, respectively. The intervals between these pulses were ~2.58 ns and ~106 ps, for SI2MF and GI2MF, respectively, and they coinside to the differential mode delays (DMDs) of the fibres,

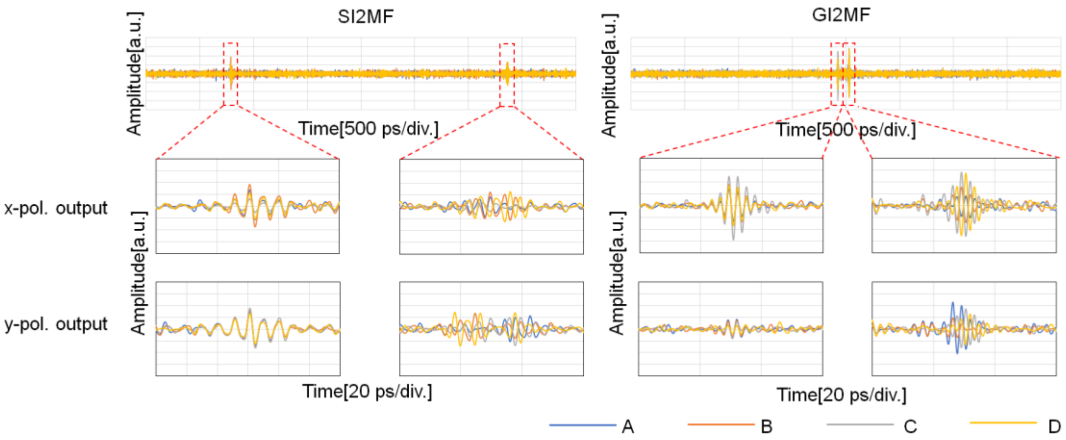

Fig. 3: The observed interference signals at eight detectors. Top: The entire impulse responses for SI2MF and GI2MF. Bottom: Zooms of the leading and latter pulses for each fibre.

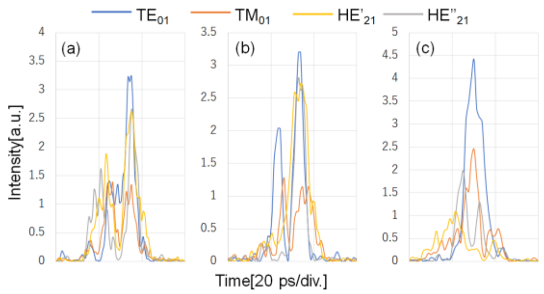

Fig. 4: Intensities of the decomposed true eigenmodes of the latter pulse (LP_{11} mode) in SI2MF. (a)-(c) show three identical measurements conducted at a 30-min. interval.

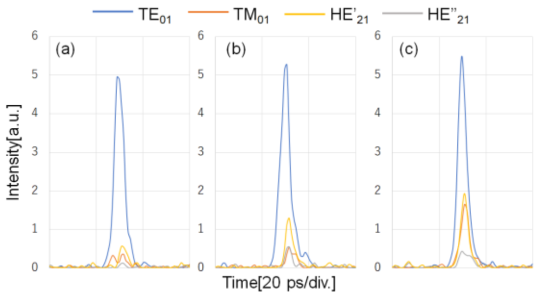

Fig. 5: Intensities of the decomposed true eigenmodes of the latter pulse (LP_{11} mode) in GI2MF. (a)-(c) show three identical measurements conducted at a 30-min. interval.

which were measured earlier. The bottom four diagrams for each FUT are the enlarged views of the leading and latter pulses. Note that the chromatic dispersion was numerically removed from the results. In both of the FUTs, the fringes observed by each detector for the LP_{01} mode agreed well with each other, whereas those for the LP_{11} mode did not. These results are reasonable considering that the electric field distributions are circumferentially uniform and non-uniform patterns, in the LP_{01} and LP_{11} modes, respectively.

Figs. 4 show the results of the modal decomposition for the latter pulse, namely, the LP_{11} mode pulse, in the SI2MF. The amplitude of each eigenmode, $c(t)$, was calculated by Eq. 1, and the powers ($|c(t)|^2$) of the eigenmodes are plotted. (a)-(c) show the results of three identical measurements conducted at an interval of 30 minuites. It was observed that the arrival time of each eigenmode differs to each other, resulting in inducing an entire pulse spread of approximately 20 ps. Moreover, the observed spatiotemporal profile randomly varied through (a)-(c), namely, with the passage of time. It is assumed that the pulse spread was induced by the intramode group delay difference in the LP_{11} mode group, and strong intramode coupling exsits in the mode group.

The results of the same results in the GI2MF are shown in Fig. 5. In contrast to SI2MF, the observed intramodal dispersion of the LP_{11} pulse was much smaller than that in SI2MF.

Conclusions

Two-dimensional linear optical sampling was applied for observing the impulse responses of SI2MF and GI2MF. Spatial-temporal profiles of in 2-LP mode fibre were observed with a ps-level time resolution. The fundamental limit of the time resolution is merely determined by the pulsewidth or spectral bandwidth of the probe and sampling lasers, whereas the requirement for accuracy of their repetition control becomes strict for achieving the fine equivalent sapling interval. For scaling the number of pixels, the use of the high-speed camera [18] which provides over a 100-kHz sampling rate with ~100 pixels would be promising.

Acknowledgements

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References

[1] D. J. Richardson, J. M. Fini and L E. Nelson," Space-division multiplexing in optical fibres" Nature Photonics, vol. 7, pp. 354-362, 2013.

[2] [4] B. J. Puttnam, G. Rademacher, and R. S. Luís, "Space-division multiplexing for optical fiber communications," Optica, vol. 8, no. 9, pp. 1186-1203, Sep. 2021.

[3] N. K. Fontaine, R. Ryf, M. A. Mestre, B. Guan, X. Palou, S. Randel, Y. Sun, L. Grüner-Nielsen, R. V. Jensen, and R. Lingle, Jr., "Characterization of space-division multiplexing systems using a swept-wavelength interferometer" presented at Conf. Opt. Fiber Commun Expo./Nat. Fiber Opt. Eng. Conf., Mar. 2013 Anaheim, CA, USA, paper OW1K.2.

[4] S. Rommel, J. M. D. Mendinueta, W. Klaus, J. Sakaguchi, J. J. V. Olmos, Y. Awaji, I. T. Monroy, and N. Wada, "Few-mode fiber, splice and SDM component characterization by spatially-diverse optical vector network analysis," *Opt. Exp.*, vol. 25, no. 19, pp. 22347-22361, sep. 2017.

[5] M. Mazur, N. K. Fontaine, R. Ryf, H. Chen, L. Dallachiesa, T. Ohtsuka, H. Sakuma, T. Hayashi, T. Hasegawa, H. Tazawa, and D. T. Neilson, "Transfer matrix characterization and mode-dependent loss optimization of packaged 7-core coupled-core EDFA," presented at the Eur. Conf. Opt. Commun., Sep. 2021, Bordeaux, France, paper Tu3A.6.

[6] J. W. Nicholson, A. D. Yablon, S. Ramachandran, and S. Ghalmi, "Spatially and spectrally resolved imaging of modal content in large-mode-area fibers," Opt. Exp. vol. 16, no. 10, pp. 7233-7243, May 2008.

[7] M. Uyama, M. Uno, S. Okamura, C. Zhang, F. Ito, A. Nakamura, T. Okamoto, and Y. Koshikiya, "Wideband impulse response measurement of coupled 2-core fibers of various lengths employing dual-comb coherent sampling," presented at the Opt. Fiber Commun. Conf., Mar. 2022, San Diego, CA, USA, (with On-line), paper M1E.5.

[8] R. Maruyama, N Kuwaki, S. Matsuo, and M. Ohashi, "Two mode optical fibers with low and flattened differential modal delay suitable for WDM-MIMO combined system," Opt. Exp. vol. 22, no. 12, pp. 14311-14321, June, 2014.

[9] T. Mori, T. Sakamoto, M. Wada, T. Yamamoto, and F. Yamamoto, "Low DMD four LP mode transmission fiber for wide-band WDM-MIMO system," presented at Conf. Opt. Fiber Commun Expo./Nat. Fiber Opt. Eng. Conf., Mar. 2013 Anaheim, CA, USA, paper OTh3K.1.

[10] R. Ryf, A. H. S. Randel, A. H. Gnauck, C. Bolle, A. Sierra, S. Mumtaz, M. Esmaeelpour, E. C. Burrows, R. Essiambre, P. J. Winzer, D. W. Peckham, A. H. McCurdy, and R. Lingle, Jr, "Mode-Division Multiplexing Over 96 km of Few-Mode Fiber Using Coherent 6 × 6 MIMO Processing" Journal of Lightw. Technol. vol. 30, no.4, pp. 521-531, 2012.

[11] D. Gloge, "Weakly Guiding Fibers" Appl. Opt. vol. 10, no.10, pp. 2252-2258, 1971.

[12] H. Kogelnik and P. J. Winzer, "Modal birefringence in weakly guiding fibers," L. Lightw. Technol. vol. 30, no. 14, pp. 2240-2245, July 2012.

[13] T. Umezawa, T. Sakamoto, A. Kanno, N. Yamamoto, and T. Kawanishi, "High Speed 2-D Photodetector Array for Space and Mode-Division Multiplexing Fiber Communications" Journal of Lightw. Technol. vol. 36, no.17, pp. 3684-3692, 2018.

[14] P. Zhu, R. Jafari, T. Jones, and R. Trebino, "Complete measurement of spatiotemporally complex multi-spatial-mode ultrashort pulses from multimode optical fibers using delay-scanned wavelength-multiplexed holography," Opt. Exp. vol. 25, no. 20, pp. 24015-24032, Oct. 2017.

[15] C. Dorrer, C. R. Doerr, I. Kang, R. Ryf, J. Leuthold, and P. J. Winzer, "Measurement of eye diagrams and constellation diagrams of optical sources using linear optics and waveguide technology," J. Lightw. Technol., vol. 23, no. 1, pp. 178–186, Jan. 2005.

[16] K. Okamoto and F. Ito, "Dual-channel linear optical sampling for simultaneously monitoring ultrafast intensity and phase modulation" J. Lightw. Technol. vol. 27, no.12, pp. 2169-2175, 2009.

[17] S. Okamura, K. Osawa, C. Zhang, F. Ito, A. Nakamura, and Y. Koshikiya, "Ultrafast measurement of vector spatial modes by using 2-dimensional linear optical sampling," Opt. Lett., accepted for publication, 2023.

[18] https://www.xenics.com/