Remote Digital Holographic Characterization of a 75.2 km Few-Mode Fiber without Reference Wave Transfer

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Abstract: We characterized inter-mode-group crosstalk of 75.2-km-long three-mode fiber transmission lines with a full-field digital holography system in which a reference wave is "remotely" generated at the output side by utilizing optical injection locking.

1. Introduction

Space-division multiplexing (SDM) has been intensely researched for the past decade as a promising ultra-high-capacity transmission technology [1]. Among SDM fibers, few-mode fibers (FMFs) can achieve high mode density with the same cladding diameter as single-mode fibers [2]. One challenge for FMF transmission is the development of techniques to characterize FMF transmission lines, because characteristics such as crosstalk between spatial modes of a transmission line can directly affect capacity and required computational complexity of digital signal processing (DSP) for the signal demodulation [3]. Although the DSP can be used to obtain the linear characteristics of the transmission line [3], it cannot evaluate transmission lines for which the transceivers have not been developed. Two powerful candidate methods for transmission line characterization are S^2 measurements [4] and a spatial light modulator-based MUX-DEMUX pair [5]. However, the former cannot deal with transmission lines with strong modal crosstalk, while the latter requires precise alignment of optical components. Digital holography (DH) is a promising technique that can overcome the shortcomings above [6,7]. In DH, one captures the interference pattern between a mode-multiplexed light (object wave) transmitted through a transmission line under test and a plane wave (reference wave) that maintains coherence with the object wave by a 2D camera. The interference pattern is then analyzed to obtain the complex amplitude profile of the object wave. Since the complex profile can be decomposed into orthogonal modes in transmission fibers such as linearly polarized (LP) modes, we can easily obtain the linear characteristic of the transmission line with DH (in this work, we focus on LP modes among such modes).

However, for characterization of >10-km-long transmission lines, the applicability of DH has been hindered due to the need to maintain the coherence of the object and reference wave. As shown in Fig. 1(a), in a conventional configuration, an auxiliary fiber with the same length as the transmission line is required to transfer the coherent reference wave, making it difficult to apply DH to deployed transmission systems. Narrow linewidth lasers have successfully shown their potential to ease the coherence length limitation [7], but that still requires an auxiliary fiber and is difficult to adapt to deployed systems.

In this study, inspired by a previous technique proposed in the field of optical frequency distribution [8], we developed a remote digital holography (RDH) system that can "remotely" work without an auxiliary fiber for the reference wave transfer. In contrast to the previous technique [8], where an optical phase-locked loop was used, we realized optical injection locking (IL) for phase-locking between an independent local oscillator (LO) and the object wave to enable DH for FMF characterization with a simple configuration, as shown in Fig. 1(b). In this study, we applied IL to full-field characterization of a transmission line consisting of a total of 75.2-km of FMF and succeeded in tracing the development of modal crosstalk at each connector point of the transmission line. We also compared the results with those obtained by conventional DH and confirmed comparable results and stability could be obtained.

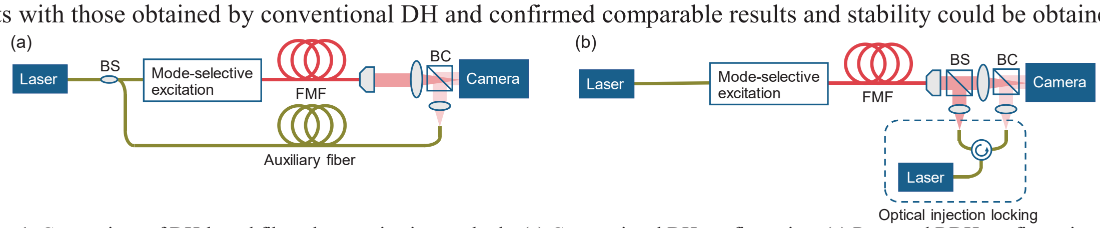

Fig. 1. Comparison of DH-based fiber characterization methods. (a) Conventional DH configuration. (c) Proposed RDH configuration. BS: beam splitter, BC: beam combiner.

2. Experimental setup

A detailed schematic of the experimental setup is shown in Fig. 2(a). Our full-field RDH system consists of two parts: a reference wave generation part using IL and an imaging part using off-axis DH. The reference wave generation part locked the phase of an LO (linewidth $\Delta f = 800$ kHz) to that of the object wave. For IL, the object wave was tapped from the imaging part with a beam splitter (BS) and injected to the LO using an optical circulator. Before the injection, the tapped object wave was amplified using an erbium-doped fiber amplifier (EDFA), accompanied by an optical band-pass filter (OBPF) and a polarization stabilizer (PS) with a tracking speed of 32π rad/s, and monitored by a polarization beam splitter (PBS) and power meter (PM). In the imaging part, the near-field light pattern at the output facet of the FMF under test was projected to an InGaAs camera by a beam expansion system with magnification of 37.5. We used a BS to combine the object wave with the reference wave. To capture full-field profiles, we prepared two reference waves with mutually orthogonal polarization and different incident angles [9]. We generated them by collimating the linearly polarized reference wave with a lens of 100-mm focal length and then splitting it with a BS. We used a half-wave plate to make one of them orthogonally polarized to the other and recombined them by using another BS with different angles adjusted by mirrors. The interference profiles captured by the camera with the exposure time of 20 μs were processed to retrieve the full-field profile, as in conventional off-axis DH [9].

First, we launched a light at 1547.19 nm from a laser (Δf = 100 kHz) into coiled graded-index FMFs and characterized the output light using RDH. We also prepared a conventional DH setup with a narrow linewidth laser (Δf = 20 Hz) to compare the results to those with RDH at the same optical power. We coupled the incident light to the FMFs using a mode selective MUX based on a planar lightwave circuit. Polarization of the incident light was controlled by a polarization controller (PC). Fig. 2(b) shows examples of a single-polarization interference pattern. Here, the LP_{01} mode of a 75.2-km-long three-mode transmission line, consisting of two graded-index (GI) FMFs with 24.0 and 51.2 km length [10], was selectively excited at the input. Without IL, no interference fringes were observed. On the contrary, with IL, we can clearly see an interference pattern like that obtained with the conventional DH setup.

3. Results

Figure 3(a) shows intensity profiles of measurements of lights transmitted through the 75.2-km-long transmission line by RDH as examples. In the measurement, we switched the input mode (LP_{01}, LP_{11a}, and LP_{11b}) and polarization (P and S) and measured output lights. To check the capability of our system to capture full-field complex profiles, we firstly decomposed the obtained complex profiles into sets of complex modal coefficients $c_{\mathrm{mn\,(a/b),P/S}}$ corresponding to P/S-polarized $LP_{mn(a/b)}$ modes, by computing overlap integral of the obtained profiles and ideal LP mode profiles as

$$c_{\mathrm{mn\,(a/b),P/S}} = \iint U_{\mathrm{P/S}}(x,y)\Psi^{*}_{\mathrm{mn(a/b)}}(x,y)\mathrm{d}x\mathrm{d}y, \tag{1}$$

where we define $U_{\mathrm{P/S}}(x,y)$ as the P/S-polarized complex profile obtained by the RDH, $\Psi^{*}_{\mathrm{mn(a/b)}}(x,y)$ as the complex profile of $LP_{mn(a/b)}$ modes assuming a 2LP FMF, and an asterisk as the complex conjugate. Then, to assess the effect of system imperfections such as component misalignment and aberration, we reconstructed the complex profiles using the coefficients and calculated the correlation between $U_{\mathrm{P/S}}(x,y)$ and the reconstructed profiles. Although slight differences between profiles were observed, correlations are quite high (average of 0.987) for all the modes and polarizations and comparable to those in previous reports (for example, 0.972 [11]). Thus, the proposed RDH configuration can provide high characterization quality for evaluation of 75.2-km-long transmission lines.

To see the applicability of RDH to modal crosstalk characterization, we measured point A, B, and C of the transmission lines shown in Fig. 3(b). The results are also shown in Fig. 3(b). Here, we constructed a transmission matrix of the fiber under test, where each component of the columns corresponds to $|c_{\mathrm{mn\,(a/b),P/S}}|^2$, by changing input modes/polarizations and calculating corresponding modal coefficients. Inter-mode-group crosstalk (IMGXT) was obtained by calculating the ratio of the diagonal and off-diagonal power distribution of the mode-group components.

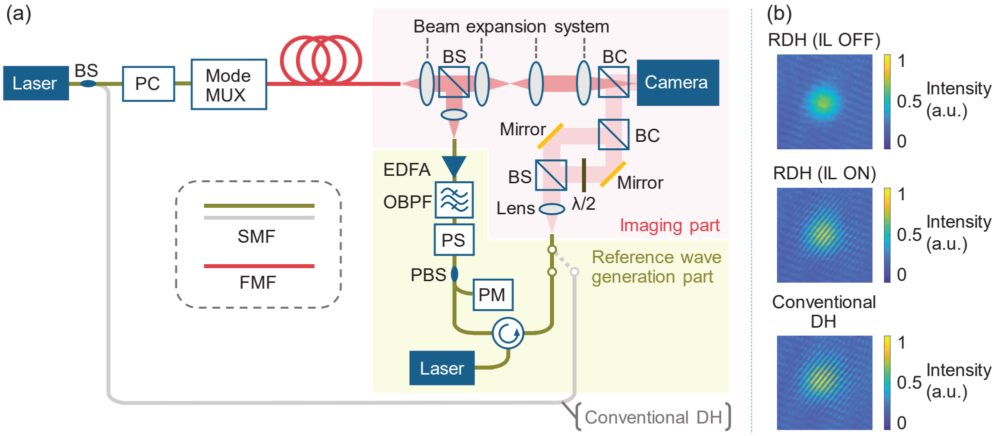

Fig. 2. Experimental setup. (a) Detailed illustration of the experimental setup. (b) Examples of obtained interference patterns with single polarization reference wave.

Note that our system contained short GI FMFs before and after the transmission line that produce additional crosstalk. We can see that the IMGXT grows along the transmission distance, which can be attributed to crosstalk of the fiber, connectors, and splice points along the transmission line. Also, the IMGXT obtained by the RDH and conventional DH were matched within 0.7 dB. Since installed transmission lines often include such sources of crosstalk, this result shows the crosstalk characterization capability of our RDH method under a condition similar to deployed systems.

We also investigated the stability of IL by continuously conducting the measurements at intervals of 1 s. The input mode was P-polarized LP_{01} mode. Here, in addition to the correlation, we evaluated the visibility of the dual-polarization interference pattern defined by

$$\text{Visibility} = \left|\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}\right|, \quad (2)$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensity of the interference pattern, respectively. The results are shown in Fig. 3(c) with corresponding interference patterns and retrieved intensity profiles of P-polarized components. Both the visibility (average of 0.892) and correlation (average of 0.990) were shown to be stable and comparable to the result for the conventional DH configuration (0.912 and 0.996, respectively).

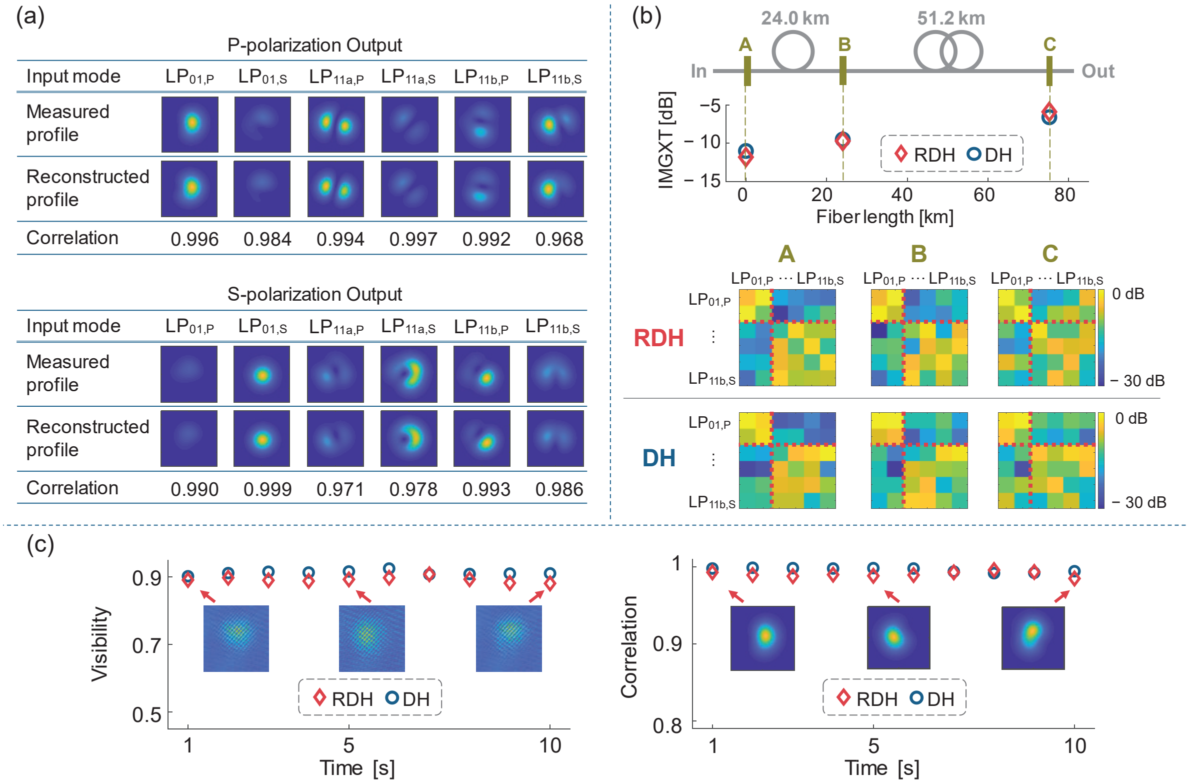

Fig. 3. Experimental results. (a) Examples of full-field measurement of light after propagation through a 75.2 km transmission line, represented by the intensity profiles. (b) Inter-mode-group crosstalk (IMGXT) of the transmission line at point A, B, and C of the transmission line and the corresponding transmission matrices. (c) Comparison of stability between the proposed RDH and conventional DH. The obtained RDH interference patterns (left) and retrieved intensity profiles of P-polarized components (right) are also shown.

4. Conclusion

In this study, we developed an RDH system using optical injection locking that enables full-field characterization of FMF without any auxiliary fiber for reference wave transfer and is thus suitable for application for deployed transmission systems. We measured crosstalk of a 75.2-km-long FMF transmission line, and successfully demonstrated the characterization with stability and quality comparable to those of a conventional configuration.

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