Theoretical Analysis and Experimental Measurement of Intra-LP-mode DMD in Weakly-coupled FMF

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Abstract: Based on the analysis of intra-LP-mode DMD in weakly-coupled FMF, we propose a modified fixed-analyzer method for its measurement and experimentally demonstrate that it may be one of the major impairments for IM/DD MDM transmission.

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1. Introduction

Recently, mode-division-multiplexing (MDM) techniques based on weakly-coupled few-mode fibers (FMF) has attracted widely interests especially for short-reach transmission [1]. The latest researches show that conventional intensity modulation and direct detection (IM/DD) can be highly compatible with weakly-coupled MDM transmission [2-3]. In such systems, weakly-coupled ring-core FMFs are adopted to separate each linearly-polarized (LP) mode one by one, and then a degenerated-mode-selective coupler can be utilized to demultiplex each pair of degenerate $LP_{mn,a}$ and $LP_{mn,b}$ modes simultaneously and realize digital signal processing (DSP)-free detection without any hardware modifications for commercial SFP+ optical modules [2]. In this paper, we investigate the influence of intra-LP-mode DMD for the DSP-free IM/DD MDM systems. In fact, the LP modes in FMF are pseudo modes consisting of eigenmodes with similar effective refractive index (n_{eff}) when the weakly-guiding condition is satisfied [4]. However, weakly-coupled FMFs with large numbers of accommodated LP modes may have a significant refractive index difference between fiber core and cladding ($\Delta n = (n^2_{core} - n^2_{clad})/(2n^2_{core})$) to realize a large minimum effective refractive index difference ($\min|\Delta n_{eff}|$) among all the LP modes to suppress the inter-LP-mode crosstalk [3]. Consequently, the degeneracy of eigenmodes inside each LP mode will decrease, which leads to differential mode delay (DMD) within each group of degenerate modes, denoted as intra-LP-mode DMD. The accumulation of the intra-LP-mode DMD will induce inter-symbol interference (ISI) and degrade the transmission performance for DSP-free IM/DD MDM transmission.

In this paper, we firstly analyze the generation of intra-LP-mode DMD, and then propose for the first time a modified fixed-analyzer (FA) method [5] to measure the intra-LP-mode DMD of each LP mode in weakly-coupled FMFs. We establish the experimental setup for the intra-LP-mode DMD measurement of a weakly-coupled 6-LP-mode FMF. Experimental results show that the intra-LP-mode DMDs of circularly-symmetric LP modes may be similar to polarization mode dispersion (PMD) of standard single-mode fiber (SSMF), while it may be much larger for non-circularly-symmetric LP modes and become one of the major impairments for IM/DD MDM transmission.

2. Principle of the intra-LP-mode DMD measurement method

As we know, there are two kinds of LP modes in a weakly-coupled FMF. The first one is circularly-symmetric LP_{0n} (n = 1, 2, 3, …) mode, which corresponds to eigenmode HE_{1n} (n = 1, 2, 3, …) and has a 2-fold degeneracy of polarizations. In theory, the two polarizations of LP_{0n} (n = 1, 2, 3, …) should have the same n_{eff}, but the imperfections of fiber fabrication and unintended perturbations may introduce slight Δn_{eff} between them. For example, the PMD between the two polarizations of LP_{01} mode in conventional SSMF is a well-known intra-LP-mode DMD. The second one is non-circularly-symmetric LP_{mn} modes (m > 0), which are the superposition of TE_{0n}, TM_{0n} and HE_{2n} modes (m = 1) or $EH_{m-1,n}$ and $HE_{m+1,n}$ modes (m ≥ 2) [4]. Each non-circularly-symmetric LP_{mn} mode has a totally 4-fold degeneracy including polarization modes. Although these eigenmodes in the same LP_{mn} (m > 0) modes are considered to be degenerate under weakly-guiding condition ($\Delta n \ll 1$), the Δn_{eff} inside each degenerate mode group always exists. Therefore, whether fiber fabrication imperfections and unintended perturbations exist or not, the intra-LP-mode DMDs of non-circularly-symmetric LP modes are inherent. For better understanding, we calculate the $\max|\Delta n_{eff}|$ inside each LP mode at 1550-nm for a step-index circularly-core (SI-CC) 6-LP-mode fiber with the normalized frequency ($V = kan_{core}(\Delta n/2)^{1/2}$) of 5.95 by the finite element method (FEM). As shown in Fig. 1, we can see that the $\max|\Delta n_{eff}|$ inside each non-circularly-symmetric LP_{mn} mode (m > 0) become non-negligible with the increase of Δn. When Δn is 2%, the $\max|\Delta n_{eff}|$ inside LP_{31} mode has even reached 1×10^{-4} which is comparable with the $|\Delta n_{eff}|$ of orthogonal polarization modes in typical polarization-maintaining fibers (PMFs).

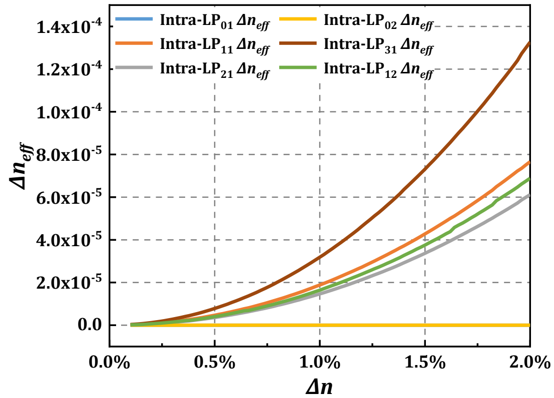

Fig. 1. The intra-LP-mode max$|\Delta n_{eff}|$ in terms of Δn for a SI-CC 6-LP-mode fiber.

Similar to the PMD measurement in SSMFs [5], we propose a modified FA method for the measurement of intra-LP-mode DMD. The experimental setup in Fig. 2 (a) is for typical PMD measurement, in which a beam of light passes through a polarizer, the SSMF and another polarizer (acting as an analyzer), and then is detected as a function of wavelength $I(\lambda)$ by optical spectrum analyzer (OSA). Considering the relationship between PMD and the frequency dependence of output polarization state, the mean PMD can be estimated by counting peaks and valleys in the intensity spectrum $I(\lambda)$:

$$E(\Delta\tau) = \frac{\rho N_e \lambda_a \lambda_b}{2(\lambda_a - \lambda_b)c} \tag{1}$$

where $E(.)$ represents statistical averaging; N_e is the number of peaks and valleys measured over the wavelength range from λ_b to λ_a; ρ is a mode-coupling constant, and in general, it is usually chosen to be 0.805 so that the mean DMD can be accurately estimated as the modal coupling is strong [6].

For eigenmodes consisting the same non-circularly-symmetric LP modes in weakly-coupled FMFs, their traverse spatial profile can always be represented by the superposition of spatial orthogonal $LP_{mn,a}$ and $LP_{mn,b}$ modes (m > 0). For example, the $HE_{m+1,n}$ and $EH_{m-1,n}$ modes are the degenerate group inside the LP_{mn} mode (m > 1), whose electrical field can be expressed as:

$$\begin{cases} \mathbf{\Phi}_{\mathrm{HE}}(r,\varphi,z,\omega) = \dfrac{u_{\mathrm{HE}}(z,\omega)}{\sqrt{2}}\left[F_a(r,\varphi)\hat{x} + F_b(r,\varphi)\hat{y}\right]e^{-j\beta_{\mathrm{HE}}(\omega)z} \\ \mathbf{\Phi}_{\mathrm{EH}}(r,\varphi,z,\omega) = \dfrac{u_{\mathrm{EH}}(z,\omega)}{\sqrt{2}}\left[F_a(r,\varphi)\hat{x} - F_b(r,\varphi)\hat{y}\right]e^{-j\beta_{\mathrm{EH}}(\omega)z} \end{cases} \tag{2}$$

where $F(r,\varphi)$ is the normalized traverse spatial profile of LP_{mn} mode; $\beta(\omega)$ is the propagation constant of each eignmode; $u(z,\omega)$ is the complex amplitude of each eignmode. If we only excite the LP_{mn} mode at the transmitter end and neglect the inter-LP-mode crosstalk, the light wave along the weakly-coupled FMF can be expressed as $\mathbf{\Phi}_{\mathrm{HE}} + \mathbf{\Phi}_{\mathrm{EH}}$. On the basis of this, the electrical field of $LP_{mn,a}$ and $LP_{mn,b}$ modes at the receiver end can be expressed as:

$$\begin{cases} \mathbf{\Phi}_a(r,\varphi,L,\omega) = \dfrac{e^{-j\beta_{\mathrm{HE}}(\omega)L}}{\sqrt{2}}\left[u_{\mathrm{HE}}(L,\omega) + u_{\mathrm{EH}}(L,\omega)e^{-j\Delta\beta(\omega)L}\right]F_a(r,\varphi)\hat{x} \\ \mathbf{\Phi}_b(r,\varphi,L,\omega) = \dfrac{e^{-j\beta_{\mathrm{HE}}(\omega)L}}{\sqrt{2}}\left[u_{\mathrm{HE}}(L,\omega) - u_{\mathrm{EH}}(L,\omega)e^{-j\Delta\beta(\omega)L}\right]F_b(r,\varphi)\hat{y} \end{cases} \tag{3}$$

$$\Delta\beta(\omega) = \beta_{\mathrm{HE}}(\omega) - \beta_{\mathrm{EH}}(\omega)$$

where L is the transmission distance. From (3), similar to one fixed polarization orientation in SMFs, we can see that the power of $LP_{mn,a}$ and $LP_{mn,b}$ modes at the receiver is determined by the relative phase difference $\Delta\beta(\omega)L$ and the complex amplitude of each eignmode, which depends on the initial conditions and the intra-LP-mode coupling. The $\Delta\beta(\omega)$ is a function of angular frequency ω because of the chromatic dispersion, which leads to the frequency dependence of the relative phase difference and intra-LP-mode coupling. Consequently, the received optical power of $LP_{mn,a}$ and $LP_{mn,b}$ modes also varies with wavelengths. Thus, the DMD inside each non-circularly-symmetric LP mode caused by inherent intra-LP-mode $|\Delta n_{eff}|$ and intra-LP-mode coupling can be reflected in the frequency-dependent power fluctuations of $LP_{mn,a}$ and $LP_{mn,b}$ modes over the measured wavelength range at the receiver. For LP_{mn} (m = 1) mode, the principle is similar. Meanwhile, only one of $LP_{mn,a}$ and $LP_{mn,b}$ modes can pass through the mode selective coupler (MSC) acting as a mode converter, which allows it to perform like a polarizer [7]. Moreover, the MSC is insensitive to output polarization state, which avoids the interference of orthogonal polarization modes.

For circularly-symmetric LP modes, the intra-LP-mode DMD is similar to the PMD in SSMFs. For DMD measurement inside LP_{0n} modes, only non-polarization-selective MSCs are needed to implement mode conversion compared to the PMD measurement for SSMFs. The setups of the intra-LP-mode DMD measurement for non-circularly-symmetric LP modes and circularly-symmetric LP modes are illustrated in Fig. 2 (b-c).

3. Experimental measurement of intra-LP-mode DMD

The FMF under test is a weakly-coupled 6-LP-mode double-ring-core fiber with Δn of 0.748% [3], and the SSMF under test is YOFC FullBand® G.652 SMF. Both fibers are fabricated by plasma chemical vapor deposition (PCVD) technique. Considering the limited space and similarities, we only present the normalized optical spectrum detected by OSA for the measurement of SSMF's PMD and intra-LP_{11}-mode DMD as examples in Fig. 2 (d-e). The measured wavelength range is from 1534-nm to 1567-nm, and the OSA's resolution is 0.02-nm. The measured intra-LP-mode DMD coefficients along with the measured PMD coefficient of SSMF over 100-km fiber are listed in Table 1. It should be noted that the modified FA method is only suitable for weakly-coupled FMF with low inter-LP-mode crosstalk. Since the distributed inter-LP-mode crosstalk coefficients among all the modes are less than -28.5dB/km for the 6-LP-mode FMF under test, we can neglect the influence of inter-LP-mode crosstalk for the intra-LP-mode DMD measurement.

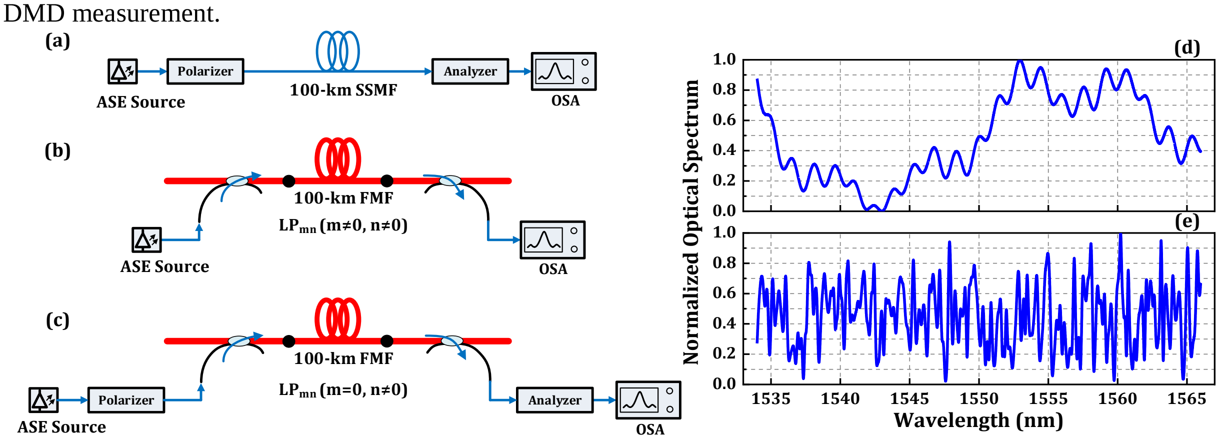

Fig. 2. The setup of FA technique for (a) PMD measurement; (b) intra-LP-mode DMD measurement for non-circularly-symmetric LP modes; (c) intra-LP-mode DMD measurement for circularly-symmetric LP modes. Normalized optical spectrum detected by OSA for (d) SSMF's PMD measurement; (e) intra-LP_{11}-mode DMD measurement.

Table 1. Measured intra-LP-mode DMD coefficients

	SSMF	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
Intra-LP-mode DMD coefficients [$\times ps/km^{1/2}$]	0.11	0.11	3.10	3.22	0.16	3.80	3.53

Here, the eigenmodes consisting the same LP modes in our weakly-coupled FMFs are strongly-coupled as the intra-LP-mode max$|\Delta n_{eff}|$ of about 1×10^{-5} is small enough. Thus, the intra-LP-mode DMD is considered proportional to the square root of transmission distance [8] just like the PMD of SSMFs. From Table 1, we can see that the intra-LP-mode DMD coefficients of LP_{01} and LP_{02} modes are similar to the measured PMD of SSMF, while the intra-LP-mode coefficients of LP_{11}, LP_{21}, LP_{31} and LP_{12} modes are significantly larger than that of the circularly-symmetric modes, which could be one of the major impairments for the IM/DD MDM transmission.

4. Conclusion

Based on the analysis of the generation of the intra-LP-mode DMD, a modified FA method is proposed to measure the intra-LP-mode DMD of weakly-coupled FMF. The results indicate that the intra-LP-mode DMDs of non-circularly-symmetric LP modes are significantly larger than that of the circularly-symmetric LP modes and may induce non-negligible penalty to the performance of IM/DD MDM transmission. *This work was supported by NSFC [61771024, 61627814, 61505002, 61690194 and 61605004], Shenzhen Science and Technology Plan [JCYJ 20170412153729436, 20180227175348359, 20170817113844300], and Projects Foundation of YOFC [SKLD1708].*

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