Modified S^2 schemes for estimating differential mode group delay in polarization-maintaining few-mode fiber

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Abstract: In the mode-division-multiplexed (MDM) system, the few-mode fiber (FMF) replaces the single-mode fiber (SMF) as the transmission medium, to increase the per-fiber transmission capacity. The polarization-maintaining few-mode fiber (PM-FMF) can greatly enhance the optical communication system, since it can both preserve the polarization state and allow the transmission of multiple modes. To obtain the differential mode group delay (DMGD) value of the PM-FMF, which determines the computational complexity of the equalization algorithm at the receiver, the characterization of the fiber is essential. The conventional S^2 method, which can estimate the DMGD of the FMF, cannot be directly applied to the PM-FMF, because the dominant mode of the PM-FMF fiber cannot be determined. In this work, two new approaches are developed, for the first time to our knowledge, to measure the DMGD in the PM-FMF. The former method is to measure the DMGD in both polarization directions, and LP_{01x} and LP_{01y} are selected as dominant modes, respectively. The latter approach is to realize a simultaneous DMGD measurement of all LP modes, and only LP_{01y} is selected as the dominant mode. It is demonstrated in the experiments that a good agreement has been achieved between the measurement results from both schemes.

Keywords: differential mode group delay; polarization-maintaining few-mode fiber; spatially and spectrally resolved imaging; optical communication system

1. Introduction

Mode-division-multiplexed (MDM) systems using few-mode fibers (FMFs) have recently received much attention because of their potential to increase the per-fiber transmission capacity [1,2]. In the MDM system, each mode carries independent information, and in an ideal FMF, the modes propagate without any crosstalk [3]. However, in the practical optical fiber, the distribution of the refractive index may vary along the direction of propagation (due to the fiber drawing or macro-/micro-bending). In order to obtain the actual differential mode group delay (DMGD) value of the FMF which determines the number of required taps in the equalization algorithm at the receiver, the characterization of the fiber is essential. Since the computational complexity of the equalization algorithm scales with the total DMGD of the fiber [4], it is necessary to design a fiber with a low DMGD. This also requires the characterization of the actually produced fiber. A typical characterization method is spatially and spectrally resolved imaging (S^2), where the characteristic parameter of the DMGD is extracted according to the beat frequency generated between each mode [5,6]. Using this method, the DMGD and the mode field information of the FMF can be measured accurately [7-9]. The polarization-maintaining fiber (PMF) is one branch of special optical fibers which can maintain the state of the polarization [10]. The polarization-maintaining few-mode fiber (PM-FMF), combining the characteristics of both PMF and FMF, has been demonstrated to achieve the MIMO-free polarization- and mode-multiplexed transmission [11]. Moreover, PM-FMFs are also widely used in the field of fiber sensing, which can realize the simultaneous sensing of multiple parameters [12]. In 2019, Liu et al. proposed a modified method for simultaneously measuring the beat length of all guided modes in a PM-FMF [13], but it is still a difficult problem to realize the simultaneous measurement of the DMGD between all LP modes in PM-FMFs accurately and effectively. Traditional S^2 method cannot be directly applied in the measurement of PM-FMF, because it is impossible to determine the dominant mode of PM-FMF, and the conventional interference equation of S^2 is not applicable to the PM-FMF. Therefore, a new approach for measuring the DMGD in the PM-FMF needs to be developed.

In this work, two new schemes are proposed, for the first time to our knowledge, to measure the DMGD and the mode field in the PM-FMF, based on the modification of the S^2 method. In the former scheme, a polarizer is added to control the polarization state of the incident light. When only X- or Y-polarized light is fed into the fiber, the LP_{01x} mode or LP_{01y} mode can be chosen as the dominant mode, and all modes in a single measurement can meet the condition of light interference. Using this method, we need two measurements to complete the assessment of all LP modes. In the latter scheme, two polarizers are added in the conventional S^2 setup. The first polarizer is used to control the power ratio between the two polarization states, after the incident light enters the PM-FMF. The second polarizer is to control the polarization direction of the emitted light. Therefore, the LP_{01y} mode can be chosen as the dominant mode among all LP modes in two directions when the power of the Y-polarized ray is much higher than the power of the X-polarized ray. This can be controlled by polarizer 1. The interference equation of S^2 can then be applied since the output light of all modes has the same polarization direction. Results of the above two measurement schemes show a good agreement between each other.

2. Principle and Experimental Setup of S^2 Imaging

S^2 imaging, a typical measurement technique for characterizing fibers, based on spatially resolved spectral interference which occurs when the light in an FMF is scattered into different modes [6]. These modes propagate with different group delays. In the first method, when only X-polarized light enters the PM-FMF, we assume to have two modes: a fundamental mode LP_{01x} and a high-order mode (HOM). Their spatially- and frequency- dependent amplitudes are A_{1X} (x,y,ω) and A_{2X} (x,y,ω), respectively, which are linked via a wavelength-independent constant α(x,y), e.g. see in [5]

$$I_{2X}(x,y,\omega) = \alpha^2(x,y) I_{1X}(x,y,\omega) \quad (1)$$

If the DMGD is assumed to be independent of frequency, the spectral intensity caused by the interference between two modes can be written as

$$I_X(x,y,\omega) = I_{1X}(x,y,\omega)[1 + \alpha^2(x,y) + 2\alpha(x,y)\cos(\tau_b\omega)] \quad (2)$$

where τ_b is the period of the beat (caused by the DMGD) frequency between two modes. The Fourier transform of the spectral intensity is then

$$B_X(x,y,\tau) = [1 + \alpha^2(x,y)]B_{1X}(x,y,\tau) + \alpha(x,y)[B_{1X}(x,y,\tau - \tau_b) + B_{1X}(x,y,\tau + \tau_b)] \quad (3)$$

where B_{1X} (x,y,τ) is the Fourier transform of the optical spectrum of the LP_{01x} mode. For PM-FMFs with more than two modes in the X-polarization direction, the interference would occur between each individual mode. This will affect the measurement of the DMGD. By providing a much stronger excitation of one mode than that of all other modes at the input side, the interference between the dominant mode and a weak mode will eclipse the interference between any two weak modes [14]. Equations and the principle of the Y-polarized light can be described similarly to the X-polarized light. The schematic of the S^2 measurement system using the first approach is shown in Fig. 1.

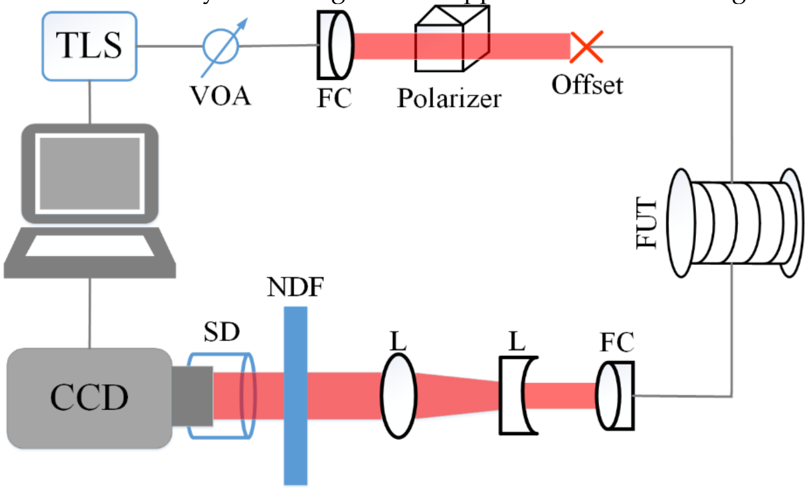

Figure 1. Schematic of the S^2 PM-FMF testbed using the first approach. FC: fiber collimator; L: lens.

Since the laser tuning works much faster than the point-to-point image scanning in the optical spectrum analyzer (OSA), in this experiment, we have employed the tunable laser source (TLS) as the light source and the charge coupled device (CCD) camera as the receiver to detect the entire spatial distribution of the light intensity. The TLS is used to produce the light wave centered at a certain frequency with the predefined tuning range and interval. The variable optical attenuator (VOA) is employed to control the intensity of the incident light (into the fiber), in order to protect the photodetector in the camera and to produce more accurate measurement results. The polarizer is to generate and manage the linearly polarized light. The polarization of the light wave is controlled to be identical as the principal axis of the PM-FMF, so that only modes in X-polarization (or Y-polarization) can pass through the fiber. A splice with offset is implemented between the single-mode fiber (SMF) and the fiber under test (FUT) in order to excite multiple HOMs. The LP_{01x} mode or LP_{01y} mode is set as the dominant mode. At the output end of the FUT, the beam is expanded using a series of lenses and is projected onto the camera. The neutral-density filters (NDF) is used to control the intensity of the optical beam to avoid saturating the detector. A shielding device (SD) is applied to mitigate the electromagnetic disturbance in front of the CCD camera. During the experiment, the CCD camera can collect the profiles of the output mode fields (at different frequencies), when the TLS is operated at the frequency sweeping mode. The data obtained by CCD are processed off-line using the computer and the final S^2 measurement results will be obtained.

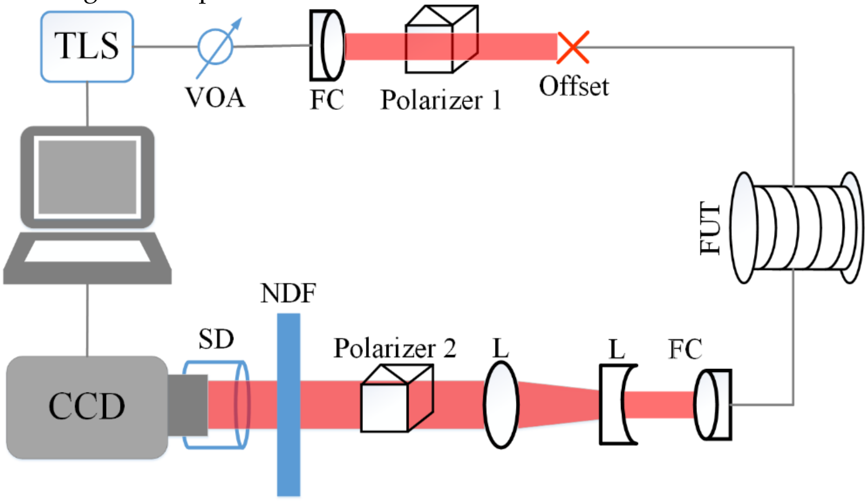

Figure 2. Schematic of the S^2 PM-FMF testbed using the second approach

Using the above structure in Fig. 1, the results will be measured when the X- and the Y-polarized light are fed into the fiber, respectively. This means that two measurements will be required to obtain a whole set of results. To measure DMGD values of all LP modes simultaneously, the polarization direction of the incident light should have components in both X- and Y-directions and the polarization direction of each mode in the output light should be identical. The block diagram of the S^2 measurement system using the second scheme is shown in Fig. 2. Polarizer 1 is again applied to generate and control the linearly polarized modes. Here polarizer 1 leaves an angle between linearly polarized modes and the principal axis of the PM-FMF to ensure the simultaneous transmission of X-pol and Y-pol modes through fibers. The power of the Y-polarized ray is much higher than that of the X-polarized ray under the control of polarizer 1. Thereby the LP_{01y} is set as the dominant mode. Polarizer 2 is employed to project all modes (output from FUT) onto the same polarization direction to satisfy the condition of interference. In terms of the system complexity, the second scheme only requires one additional polarizer, while it can achieve a simultaneous measurement of all LP modes.

3. Experiments and Results

The FUT in the experiment is a panda-type PM-FMF with a length of 10 m. We first use the experimental testbed shown in Fig. 1 to measure the S^2 results when only the X- or the Y-polarized light passes through the fiber. The tuning range of the TLS is from 192268 GHz to 194828 GHz and the tuning interval is set as 5 GHz. The CCD camera acquires images of the output light intensity as the TLS frequency is tuned. The total number of the images collected is 512. In the experiment where only X-polarized light enters the fiber, the DMGDs of all modes in the X-polarization direction can be obtained by taking the Fourier transform of the intensity spectrum. The S^2 result for the X-polarized light is shown in Fig. 3.

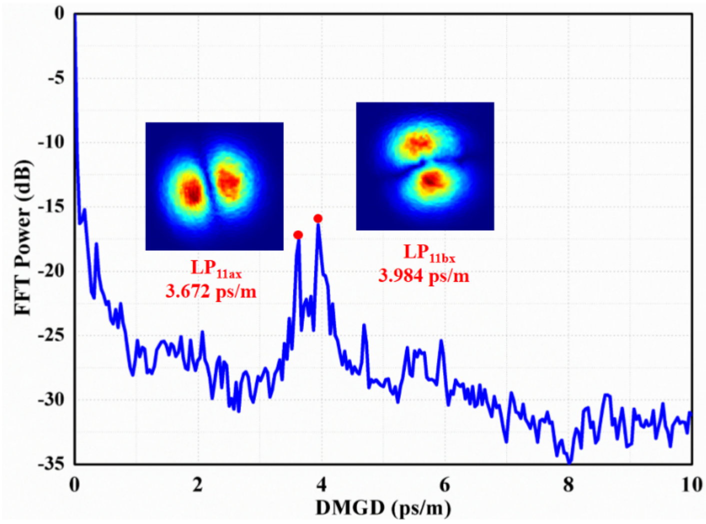

Figure 3. DMGD and mode field measurement results for the X-polarized light.

In Fig. 3, there are clearly several different discrete peaks, corresponding to interference between the fundamental LP_{01x} mode and HOMs. The DMGDs of LP_{11ax} and LP_{11bx} relative to LP_{01x} are calculated as 3.672 ps/m and 3.984 ps/m, respectively. Then for the experiment where only Y-polarized light enters the fiber, the S^2 result is shown in Fig. 4. The DMGDs of LP_{11ay} and LP_{11by} relative to LP_{01y} are calculated as 3.672 ps/m and 3.984 ps/m, respectively.

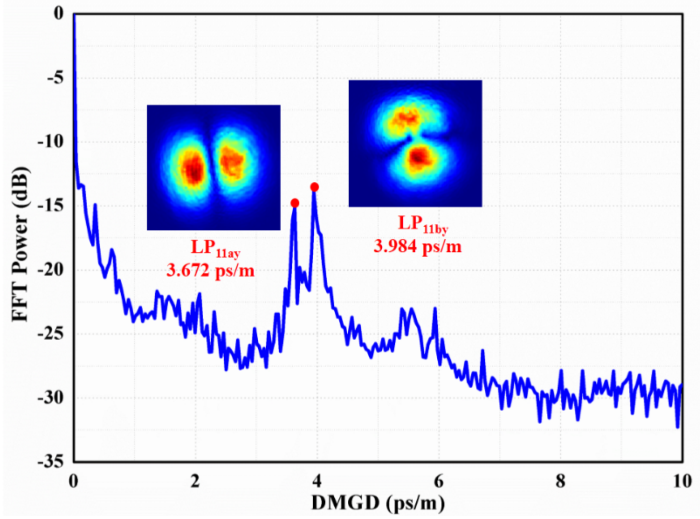

Figure 4. DMGD and mode field measurement results for the Y-polarized light.

Using the S^2 system provided in Fig. 2, we can complete the measurement of all LP modes in a single test. The DMGD and mode field measurement results are shown in Fig. 5. It can be seen from Fig. 5 that the DMGD values of LP_{01x}, LP_{11ay}, LP_{11by}, LP_{11ax} and LP_{11bx}, relative to LP_{01y}, are 1.914 ps/m, 3.672 ps/m, 3.984 ps/m, 5.547 ps/m and 5.938 ps/m, respectively. That is, the DMGDs of LP_{11ay} and LP_{11by}, relative to LP_{01y}, are 3.672 ps/m and 3.984 ps/m, the DMGDs of LP_{11ax} and LP_{11bx}, relative to LP_{01x}, are 3.633 ps/m and 4.024 ps/m. Comparing the results from the two methods, the DMGD values of LP_{11ay} and LP_{11by} are exactly the same, and the DMGD values of LP_{11ax} and LP_{11bx} are slightly different by -0.039 ps/m and 0.040 ps/m, respectively. The accuracy of the two method is over 98.9%. Therefore, the measurement results from these two methods show good agreement, and this indicates that it is feasible to use the proposed two methods to measure the DMGD in the PM-FMF.

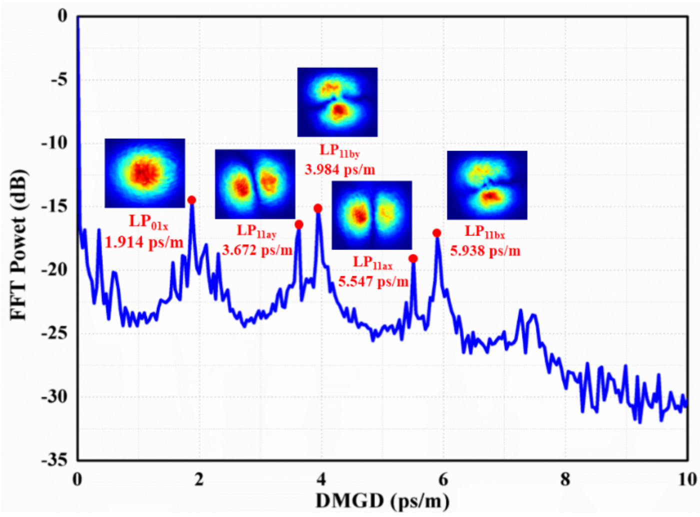

Figure 5. DMGD and mode field measurement results using the second scheme.

4. Conclusions

In this work, we have developed two new methods to measure the DMGD in the PM-FMF. It has been experimentally demonstrated that both appraoches can accurately estimate the DMGD in the PM-FMF, and measurement results from the two schemes show a good agreement. These two methods make up for shortcomings of the traditional S^2 method, in which the dominant mode cannot be determined. The former scheme selects a dominant mode for each polarization direction, and the latter scheme employs the LP_{01y} mode as the dominant mode for all LP modes. Using the second measurement scheme, we can achieve the measurement of all LP modes in the PM-FMF via a single test. Compared to the first approach, the second scheme can double the measurement efficiency, by adding only one polarizer. Therefore, we recommend the use of the second approach to measure the DMGD in the PM-FMF when experimental devices are sufficient. The characterization of fiber parameters using our proposed schemes will facilitate the design and the optimization of the PM-FMF, which will play an important role in the development of optical communication systems.

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