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Modal dispersion characterization of few-mode fiber based on electrical spectral interferometry with optical frequency comb

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A R T I C L E I N F O

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A B S T R A C T

We experimentally demonstrate a novel method based on electrical spectral interferometry with optical frequency comb for characterizing the modal dispersion between the higher-order modes and fundamental mode in a 1-*km* four-mode few-mode fiber (FMF). In this method, an optical frequency comb (OFC) is used to generate many subwavelengths with the same frequency interval to improve the measurement accuracy and speed. Based on the electrical spectral interferometry, the differential mode group delay (DMGD) and modal dispersion of the tested FMF are obtained by applying the simple FFT processing. The measured DMGD and modal dispersion within the whole C-band are about (3.2032–3.3033) *ps/m*, (2.5573–4.2085) *ps/nm.km* and (5.5055–5.7057) *ps/m*, (−11.2112–−4.1486) *ps/nm.km* and (11.1111–11.3113) *ps/m*, (−10.2454–−14.1332) *ps/nm.km* for LP11, LP21 and LP02 modes respectively. Meanwhile, we achieved a precision of ± 0.002 *ps/m* for DMGD measurement. Compared with previous methods, our method has the advantage of high measurement accuracy, simple configuration and fast speed. The experimental results show that the demonstrated method could be a good solution to the characterization of a long FMF used in large capacity mode-division-multiplexing transmission systems.

1. Introduction

With the rapid development of the data services, such as the Internet, online games, Internet of Things etc., optical fiber communication technology plays an important role to meet the increasing demands. However, optical fiber communication systems must be updated quickly and timely to improve the transmission date rate and system capacity. Recently, mode-division multiplexing (MDM) technique based on few-mode-fiber (FMF) or multicore FMF has been adopted to build ultra-large capacity of transmission system [1–5]. FMF-based MDM system is a good candidate for the large capacity transmission systems since FMF has a large amount of orthogonal fiber modes which can be used as individual channels. Meanwhile, the FMFs are designed to support limited fiber modes with special properties when compared with conventional multimode fiber (MMF). Thus, the FMF-based MDM transmission system can be adopted to both long-haul and short-reach transmission with acceptable system complexity and cost [5–7]. Therefore, the property of the used fiber, such as the differential mode group delay (DMGD) and modal dispersion relative to the fundamental mode, will play a key role in this kind of MDM systems. So, it is very important to characterize the parameters of a FMF prior to implement the transmission system and then further optimize the system performance. Besides, the characterization of a FMF or MMF is also important in other applications, such as beam characterization of fiber laser [8], multimode nonlinear dynamics [9], etc.

The existing typical methods used to characterize the FMF include the time-domain technique [10], optical low-coherence interferometry (OLCI) [11,12], and spectral interferometric techniques [13–15]. By using a temporal short pulse fed into the FMF, the relative time delays between the output modal pulses can be recorded for the time-domain-based measurement. The basic principle of OLCI measurement method is mainly based on a Michelson interferometer and a broadband incoherent optical source which can improve the spatial resolution and the sensitivity. But, the complicate experimental setups (e.g., precise moving stage) or expensive equipment (e.g., mode-locked laser, frequency swept laser or ultra-fast oscilloscope) are required for both the time-domain and OLCI based methods. However, the spectral interferometric technique has the ability to overcome these disadvantages. It merely needs a tunable light source (TLS), simple interferometer and then can acquire the FMF parameters directly from the interferogram.

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This technique, however, has also a drawback of measuring the parameters of a long FMF because of the limited length of reference arm. To realize the characterization of a long FMF with good accuracy, the coherent-detection-based method has also been applied with some sophisticated algorithms [16,17], which might not be cost-effective. Recently, the microwave interferometric technique based on a filtered amplified spontaneous emission (ASE) source has been demonstrated for characterizing a short FMF with good accuracy [18]. In general, the 3 dB bandwidth of the filtered ASE source is on the order of 10 GHz to get a relative shorter coherence time and then avoid the interference between the optical modes. So, some new methods should be studied to characterize the property of a long FMF used in large-capacity MDM transmission systems.

In this paper, we propose a scheme to characterize the long FMF based on the combination of electrical spectral interferometric technique and optical frequency comb (OFC). This method cancels the requirement of laser wavelength scanning and enables the measurement more accurate due to the unique property of wavelength stability of the optical frequency comb. The frequency shift induced by the laser source can be neglected because of the frequency-locked property of the optical frequency combs originated from the one-shared seed laser. In this demonstration, the DMGD and modal dispersion of multiple fiber modes supported by the tested 1-km FMF have been characterized with simply processing. The measured DMGD and modal dispersion are about (3.2032–3.3033) ps/m, (2.5573–4.2085) ps/nm.km and (5.5055–5.7057) ps/m, (−11.2112–−4.1486) ps/nm.km and (11.11-11–11.3113) ps/m, (−10.2454–−14.1332) for LP11, LP21 and LP02 modes respectively. Results show that the demonstrated method has the advantage of high accuracy with relative fast measurement speed and simple configuration by using the wideband optical frequency comb. This demonstration also enables the potential for characterizing a long FMF used in the next-generation optical MDM systems.

2. Principle

Fig. 1 shows the experimental setup of the proposed method to characterize a long FMF. Basically, the DMGD and modal dispersion between higher-order modes and fundamental mode are the most key parameters to be measured. The continuous wave (CW) from the TLS is fed into the OFC generator (OFCG, OptoComb WTAS-02), which can generate many carriers covering the whole C-band with the same frequency interval of 25 GHz. However, the intensity profile of the output combs from the OFCG have a triangle-shape distribution which results in the poor flatness. To better use the optical frequency comb, a wavelength selective switch (WSS, Waveshaper 4000S) is adopted to filter out the desired number of carriers and adjust the power level of these wavelengths. Note that the TLS is mainly used to act as the seed laser of the OFCG and we will have no need to tune the center wavelength and use the WSS if the quality of entire output combs can meet the measurement demands. The output optical signal is then fed into the Mach-Zehnder modulator (MZM, PHOTLINE MX-LN-40), which is modulated by a frequency-swept radio-frequency (RF) signal offered by the vector network analyzer (VNA, Keysight N5222A PNA) under proper direct-current (DC) bias voltage. An Erbium-doped fiber amplifier (EDFA) is placed after the MZM to increase the power of modulated optical signal. Then the signal is butt-coupled (BC) to the FMF using a collimator (COL) and a three-dimensional adjustable coupled stage, which has a microscopic objective (MO) and can adjust the relative launching position between the single mode fiber (SMF) and FMF easily by adjusting the knobs. By launching the optical signal onto different position at the input end of the FMF (namely, offset launching), the higher-order modes of FMF supported can be easily excited. After propagating through the FMF, the multi-wavelength optical signal with mixed different modes is coupled into the other EDFA to increase the power of output signal, and then filtered out one by one via a tunable optical band-pass filter (TOBF) (Alnair Labs BVF-300CL) and detected subsequently by a photo-detector (PD, Discovery DSC R401HG) used to demodulate the RF signal with which information is recorded by the VNA. By sweeping the frequency of RF signal within a desired range, the frequency response of the FMF at a certain wavelength can be obtained. Based on this process, we can acquire the characterization of the FMF within the desired wavelength band simply.

Based on the above description, the modulated signal with optical frequency comb used to excite the fiber modes can be expressed as follows,

$$E_s = E_{OFC}H_{MZM} = \sum_{n=1}^{N} E_n e^{j2\pi f_n t}\cdot\cos(a\cos(f_m t)) \approx \sum_{n=1}^{N} E_n[e^{j2\pi f_n t} + be^{j2\pi(f_n+f_m)t} + be^{j2\pi(f_n-f_m)t}] \quad (1)$$

where E_n, f_n and a, f_m are the amplitudes and frequencies of the nth optical subwavelength component and the drive RF signal respectively. b is the modulation index, and the frequency interval of the OFCG $f_s = f_n - f_{n-1} = 25$ GHz. In Eq. (1), the first term represents the optical carrier, while the second and third terms are the two ± 1st -order sidebands induced by the MZM. After propagating through the FMF, different frequency components will have respective delays which can be used to extract the DMGD and modal dispersion. Following the same way used in [18], the output of the ith mode of the nth wavelength filtered by the TOBF can be represented as follows,

$$E_{ni}^{out} = E_n e^{j2\pi f(t-\tau_{ni}(f))} + bE_n[e^{j2\pi(f+f_m)(t-\tau_{ni}(f+f_m))} + e^{j2\pi(f-f_m)(t-\tau_{ni}(f-f_m))}] \quad (2)$$

in which,

$$\begin{aligned}\tau_{ni}(f) &= \tau_{ni}(f_n) + D_i(f-f_n)\\ \tau_{ni}(f+f_m) &= \tau_{ni}(f_n) + D_i(f+f_m-f_n)\\ \tau_{ni}(f-f_m) &= \tau_{ni}(f_n) + D_i(f-f_m-f_n)\end{aligned} \quad (3)$$

And τ_{ni} and Di are the delay and modal dispersion of the optical component with frequency f of mode i. After the optical-to-electrical conversion by the PD, the generated electrical signal can be expressed as follows,

$$I_{out} = R\,|\sum_i E_{ni}^{out}|^2 \quad (4)$$

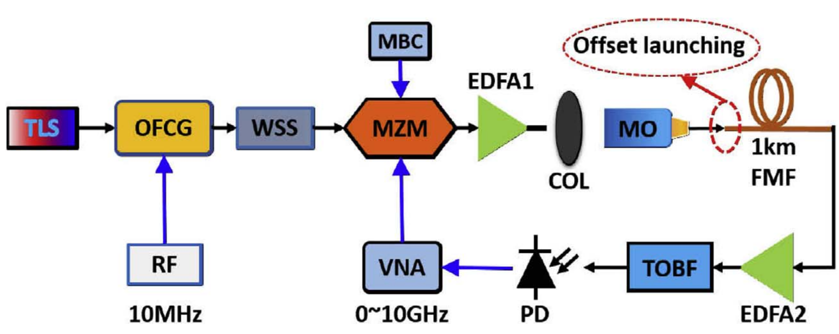

Fig. 1. Experimental setup of the proposed method. TLS: tunable light source; OFCG: optical frequency comb generator; RF: radio frequency; WSS: wavelength selective switch; MZM: Mach-Zehnder modulator; VNA: vector network analyzer; EDFA: Erbium-doped fiber amplifier; COL: collimator; MO: microscopic objective; FMF: few-mode fiber; TOBF: tunable optical band-pass filter; PD: photo-detector.