Simultaneously Measuring Group Delays, Chromatic Dispersion and Skews of Multicore Fibers Using a Frequency Domain Method

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Abstract: A frequency domain method is proposed to measure group delays, chromatic dispersion and skews of multicore fibers. We present detailed studies through measuring a 2×2 multicore fiber which agree well with the time domain method. © 2021 The Author(s)

1. Introduction

In recent years, space division multiplexing (SDM) using single-mode uncoupled multicore fibers (MCF) has been widely studied as one way to increase the capacity of optical fiber transmission systems [1]. SDM is attractive for high-throughput and high-density short-reach optical interconnects to improve the performance of large-scale datacenters [2-4] and to meet the increasing demands of future long-haul systems for ultra-high capacity and flexibility [5].

For manufacturing MCF products, simple, fast and accurate measurements with low cost are critical for practical applications. Same for standard single-mode fibers, the attenuation, mode field diameter (MFD), cutoff wavelength, chromatic dispersion (CD), and polarization mode dispersion (PMD) are important parameters to characterize for MCFs. In addition, there are parameters that are unique to MCF such as crosstalk [6,7] and skew [8,9] that need to be measured. In principle, if access can be gained for each core, the measurements of the optical properties of MCF can be done for each core just like for standard single mode fiber by treating each core as one fiber. However, the access of each core requires fan-in and fan-out devices, which adds costs to the measurement equipment and consumes more time for the measurements. Characterization techniques that can measure all cores together are highly desirable for MCF measurements.

In this paper, we propose a simple and robust frequency-domain method for characterizing MCF, which can measure group delays, CD and skews of all cores simultaneously. This method is extended from Ref. [10], which was used to measure differential mode delays of few-mode fibers. It utilizes the inverse Fourier transform of a measured complex transfer function to determine the group delays between different cores. Through proper treatment of the data, we can de-alias the signal and obtain the accurate values of the group delays of each core and the skews in the right time sequence. By measuring the group delays over different wavelength, the data can also yield the CD of each core over the wavelength window. In this paper, we present the measurement principle with experimental demonstration and comparison with time domain results.

2. Measurement Principles

In Ref. [10], a method for measuring the group delay and modal delay (defined as group delay difference between different modes) of few mode fibers has been presented. We show in this paper that the method can also be used for measuring group delays of MCF. Through a vector network analyzer (VNA) and proper E-O and O-E conversion the complex transfer function (CTF) over a frequency range for the fiber under test (FUT) at a given launch condition, which is also labelled as S_{21} can be measured. The CTF takes the form,

$$CTF(f) = S_{21}(f) = \sum_{j=1}^{n} a_j \cdot \exp(-i \cdot 2\pi f \tau_j) \qquad (1)$$

where a_j is the relative optical power in core j, and τ_j is the group delay of core j.

One can perform an inverse Fourier transform of *CTF(f)* on either the real or imaginary part of CTF as labelled $\mathcal{F}^{-1}$(real(*CTF(f)*) or $\mathcal{F}^{-1}$(imag(*CTF(f)*) to extract the time-domain information from the frequency domain measurement to obtain the group delay of each core, τ_j. Using the group delay, the skew which is defined as the difference of the group delays between cores can be calculated. The skew is also referred to as inter core skew (ICS). To fully resolve the time domain information without causing aliasing or ambiguity of the group delay time τ_j, the sampling frequency step df needs to meet the condition as set by Nyquist theorem, $df \le 1/(2 \cdot \max(\tau_1, ... \tau_n))$, which results in unreasonable large numbers of points that need to be sampled. However this problem can be solved if we apply a de-aliasing procedure that the peak value in the inversion Fourier transform is related to the actual group delay of each core τ_j by a simple equation,

$$\tau_j = (k / df) \pm t_j \qquad (2)$$

where k is an integer. Depending on the sign before t_j, the time sequence from inverse Fourier transform can either be the same time sequence or the opposite one compared to the actual propagation times for each core. With a proper choice of k based on the fiber length and estimated group index information, we can recover the propagation time with right time sequence and can de-alias the signal to obtain the full group delay τ_j for each core correctly.

3. Measurement of 2×2 MCF over O-Band

The experiment setup is shown in Fig. 1. A narrow linewidth continuous-wave light source is intensity modulated with the modulation frequency controlled by the vector network analyzer (VNA). We used a 2×2 MCF as shown in Fig. 2 (a) for the measurement. The fiber cores are standard single-mode fiber cores with mode field diameter of 8.25 µm at 1310 nm and 10.02 µm at 1550 nm. The neighboring core-to-core separation is around 41.16 µm. The fiber length is 3104 m sitting on a shipping spool. The light is launched into the MCF through an overfilled multimode fiber that is ~300 µm away from the MCF end so that the beam can expand and reach all the four cores. An air gap is also used in receiving end for better receiving light from all four cores. No fan-in and fan-out devices are used to access each core, which significantly simplifies the experimental setup and measurement procedure. The light from the launch fiber has the optical power of -6.75 dBm and the power reaching the receiver is -32.4 dBm. Despite the small amount of light coupled into the MCF cores, the VNA can still detect the light due to its high sensitivity to get the signals to recover the full information.

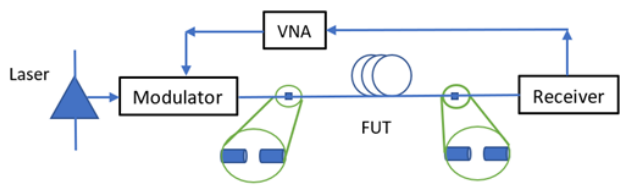

Fig. 1 Experimental setup for the frequency domain measurement.

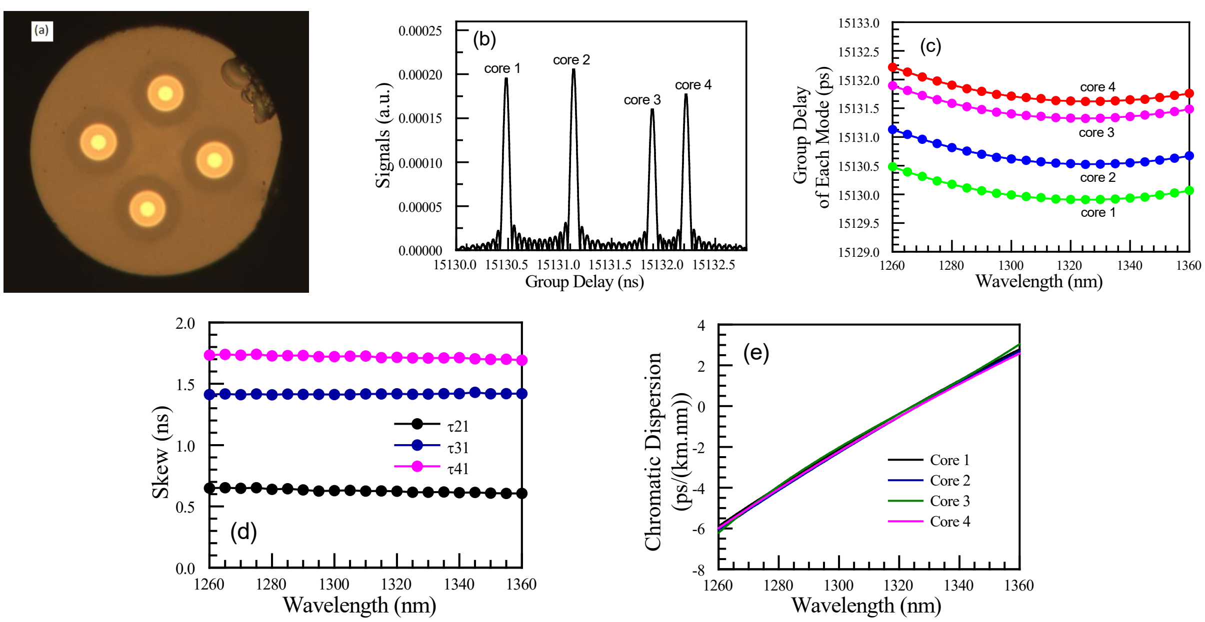

Fig. 2. (a) Cross section image of the 2×2 MCF; (b) the de-aliased time signals; (c) the measured group delays of each core over O-band; (d) the skews of the MCF over O-band; (e) the CD from each core over O-band.

In Fig. 2(b), we show the de-aliased time signal obtained from inverse Fourier transform of the real part of CTF obtained at 1260 nm with proper de-aliasing using Eq.(2). The time sequence from the inverse Fourier transform would otherwise be in a reversed order as the sign in Eq.(2) is negative. The peak locations are the group delays for each core. The four cores have well separated group delays and we label each core in the sequence in Fig. 2(b) as core 1, 2, 3 and 4. Using the procedure, we recovered the group delays of each core over the whole O-band from 1260 nm to 1360 nm with 5 nm increment as shown in Fig. 2(c) . The ICS between core 1 and each other cores are shown in Fig. 2(d) as τ21, τ31 and τ41. As can be seen the skew is the largest between the core 4 and core 1 and they stay nearly constant across the O-band. Since the procedure in Section 2 can precisely yield the group delay of each core over a wavelength range, we can obtain the chromatic dispersion of each core using the equation, $CD = d\tau / d\lambda$, where τ is the group delay of a core. The results are shown in Fig. 2(e). The cores have zero dispersion wavelengths between 1324-1326 nm and CD slopes around 0.083 ps/(nm^2·km), which agree with what were measured from commercial chromatic dispersion instrument (Perkin Elmer 500). We would also note that the measurements were done over the four cores simultaneously with very low optical power. This is a significant advantage of the method over others as the measurement can be done in a relatively simple and fast fashion.

We also measured the same MCF using a time domain setup around 1550 nm at which a high-power light source is available. Optical pulses are generated by an intensity modulator driven by an electric pulse generator with a repetition rate controlled by the clock. An optical amplifier is used to boost the optical power from -9.2 dBm at the intensity modulator output to 19.5 dBm at the output of the amplifier with the gain of 28.7 dB in order to have sufficient signals detectable by the sampling scope. The optical power reaching the optical receiver is -4.45 dBm. The output pulse trains are captured by the sample scope with results shown in Fig. 3(a). The comparison results from frequency domain is shown in Fig. 3(b). The skew results between the two methods agree quite well.

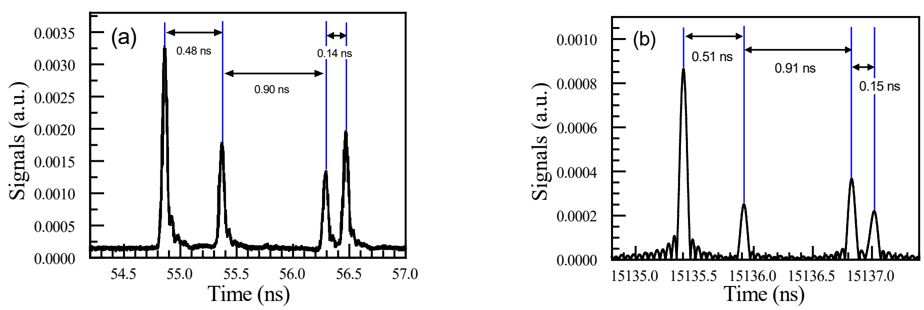

Fig. 3. (a) The output pulses measured from time domain setup around 1550 nm. (b) The de-aliased time domain signals obtained from inversed Fourier transformed of CTF around 1550 nm.

4. Conclusions

We have proposed the use of a frequency domain method to measure group delay and chromatic dispersion of each core, and the skews between cores of an MCF. We demonstrated the simultaneous measurements of these properties for a 2×2 MCF with good agreement with commercial instrument or direct time domain measurement. The measurement can be done for all cores simultaneously under very low optical power and without obvious limitation on the number of cores for the MCF.

5. References

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