A Poincare Sphere Method for Measuring Polarization-Mode Dispersion Using Four-Wave Mixing (FWM) in Single-Model Optical Fiber

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Abstract: A nonlinear Poincare sphere method for measuring polarization-mode dispersion (PMD) using the four-wave mixing (FWM) effect in single-mode optical fibers is presented. This method is based on the FWM-power transfer function on the polarization states of the input signals. Average PMD can be obtained by using this method with measurements in just a narrow optical bandwidth.

Key words: Polarization Mode Dispersion, PMD measurement, Poincare-Sphere Method, Four-wave mixing (FWM)

I. Introduction

Polarization-mode dispersion (PMD) is one of the major limiting factors of ultrahigh-bit-rate optical fiber communication systems. Currently, PMD is a big concern when upgrading legacy networks of installed fiber to 10 Gb/s (OC-192) rates and higher. For example, at 10 Gb/s (OC-192), the limit on PMD is about 10 ps [1]. Knowledge of the PMD in the fiber plant is becoming very critical for system designs, evaluations and installations.

Measuring PMD for installed fiber still is not an easy task. The time-domain methods are degraded by polarization state fluctuations, caused by polarization mode coupling in the fiber [2]. On the other hand, the frequency-domain method is limited by the motion-less condition. Any motion of the measurement apparatus, especially at the ends the fibers, can totally destroy the measured results [2, 3]. Maintaining a motionless condition is often difficult, especially with field measurements.

Recently, a novel nonlinear method was presented for measuring PMD using four-wave mixing (FWM) [4]. It alleviated the strict requirement for a motion-less condition. This paper presents a new technique for measuring PMD that is based on the same nonlinear effect (four-mixing, FWM) as in [4], but uses the Poincare sphere method to calculate PMD. In this method, two signals at different frequencies are launched into the fiber under tested. The output signals are then input to a dispersion-shifted fiber (DSF) to produce FWM. The FWM power in the DSF is related to the arc length on the Poincare sphere and is measured to determine the PMD value of the fiber under test. Theoretically, this method can produce a PMD value from each measurement point on FWM power, thus it greatly reduce the signal wavelength scanning range in the optical spectrum, though multiple measurements may be still needed to reduce the influence of FWM power fluctuation.

II. The theory of the method

FWM is a nonlinear process induced by Kerr effect in optical fiber. If three signals at frequencies f_i , f_j and f_k co-propagate through a single-mode fiber, the new frequency generated through FWM would be $f_l = f_i + f_j - f_k$. For the partially degenerate case, $f_i = f_j$, the newly generated frequency is $f_l = 2f_i - f_k$. The generated FWM power depends not only on the signal frequency separations, input signal power and fiber loss and nonlinear characteristics [5, 6, 7], but also on the input signal polarization states [4, 8]. The FWM power transfer function on the state of polarization (SOP) of the input pump signals can be written as [4]

$$F(SOP_1, SOP_2) = \frac{1}{2}[1 + \bar{s}_1(\omega_1) \cdot \bar{s}_2(\omega_2)]$$
$$= \frac{1}{2}[1 + s_1^{(1)} s_1^{(2)} + s_2^{(1)} s_2^{(2)} + s_3^{(1)} s_3^{(2)}] \tag{1}$$

Where $\bar{s}_1(\omega_1) = [s_1^{(1)} \quad s_2^{(1)} \quad s_3^{(1)}]^T$ and $\bar{s}_2(\omega_2) = [s_1^{(2)} \quad s_2^{(2)} \quad s_3^{(2)}]^T$ are the normalized vectors representing the two polarization states of the two input signals at frequencies ω_1 and ω_2, repectively. (1) is valid when the PMD in the fiber (measurement fiber) is small. This transfer function has been verified by both simulation and experiments in [4].

On the surface of Poincare sphere, we can write (1) as

$$F(s) = \frac{1}{2}[1 + \cos(\phi)]$$
$$= \frac{1}{2}[1 + \cos(s)] \tag{2}$$

where ϕ is the angle between the two polarization vectors and s is the arc length between the two end points of the two polarization vectors on the Poincare sphere. From (2), we can write s as a function of F, that is

$$s = \cos^{-1}(2F - 1) \tag{3}$$

By definition, the first-order PMD is calculated by [9]

$$PMD = \left| \frac{ds}{d\omega} \right| \tag{4}$$

where ω is the signal angular frequency. Substituting (3) into (4), we get

$$PMD = \frac{1}{\sqrt{F(1-F)}} \left| \frac{dF}{d\omega} \right| \tag{5}$$

If we use wavelength instead of frequency, (5) becomes

$$PMD = \frac{\lambda^2}{2\pi c \sqrt{F(1-F)}} \left| \frac{dF}{d\lambda} \right| \tag{6}$$

where λ is the wavelength and c is the speed of light.

The FWM transfer function, F, is obtained by measuring the FWM efficiency as a function of the signal wavelength separation. In real measurements, F needs to be calibrated with the zero-PMD case to reduce the effects of chromatic dispersion in measurement fiber. The derivative in (6) should also be replaced by a difference equation and we get

$$PMD = \frac{\lambda^2}{2\pi c \sqrt{F(1-F)}} \left| \frac{\Delta F}{\Delta \lambda} \right| \tag{7}$$

where ΔF is the change in FWM efficiency inside the small wavelength window $\Delta\lambda$. To reduce the influence of FWM power fluctuation, multiple measurements are needed either at one wavelength or at multiple wavelengths.

III. Experimental results

An experimental setup for measuring PMD using FWM is shown in Fig. 1. Here, a PMD emulator was used to generate a known amount of PMD in the system and served as the fiber under test. A 17.5-km dispersion shifted fiber (DSF) with a zero-dispersion wavelength of 1551 nm was used as the measurement fiber to produce FWM. The FWM power was measured by an optical spectrum analyzer. In our measurements, the wavelength of one input signal was fixed at 1554.0 nm, and the other signal wavelength was varied, where the range of variation chosen depended on the expected PMD values. During measurements, the PMD emulator was first set to zero PMD and the FWM efficiency was measured and recorded, where the FWM efficiency is defined as the FWM power normalized by its maximum value which occurs when the polarization states of two input signals are aligned. This data was used for calibrating the FWM efficiencies for the non-zero PMD cases. Fig. 2(a) and (b) show the measured FWM efficiency vs. the signal wavelength separation for two PMD values, 10 ps and 20 ps, after calibration. The PMD-induced periodic variations on FWM power is clearly observed when signal wavelength is swept. The minimum measurable FWM level was limited by ASE noise.

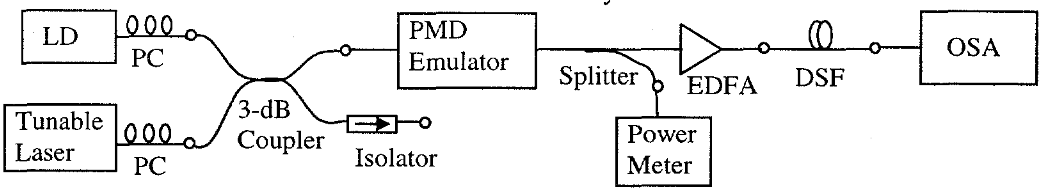

Fig. 1 Experimental setup for measuring PMD using FWM.
LD--Laser diode; PC--Polarization controller; EDFA--Erbium-doped fiber amplifier; DSF--Dispersion-shifted fiber; OSA--Optical spectrum analyzer

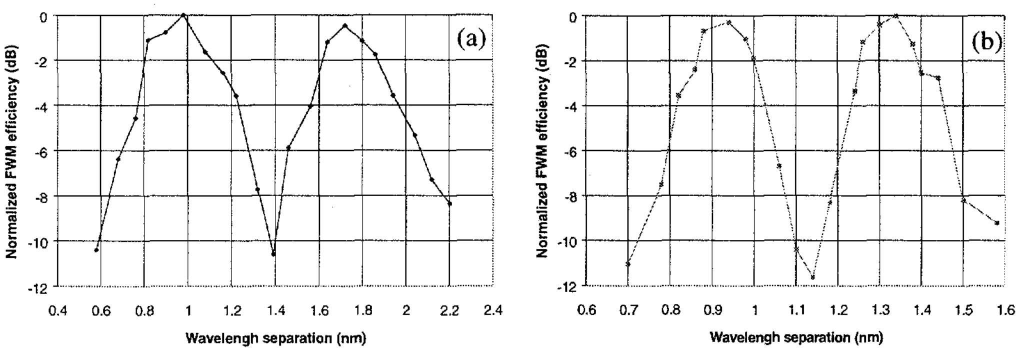

Fig. 2 Normalized FWM efficiency for PMD =10 ps and PMD = 20 ps after calibrated with zero-PMD case. (a) PMD = 10 ps, (b) PMD = 20 ps.

Fig. 3 shows measured average PMD for different given PMD. The measured mean PMD values were obtained by averaging the measurements in different wavelength ranges, represented by the periods of variations of FWM efficiency on wavelength, as show in Fig. 2. Four cases in Fig. 3 correspond to 0.5, 1, 1.5 and 2 periods. The measured results for all four cases follow well with the given values, but are mostly a little bit lower than the true PMD. This is due to measurement errors around the notch areas of the measured FWM efficiency curve. Theoretically, the notches of the FWM efficiency curve should have approached zero, but in experiments these points are non-zero due to the amplified spontaneous emission in the erbium-doped fiber amplifier (EDFA).

To estimate the optical bandwidth needed for this method, Table 1 gives the calculated width in nanometer for each period of the FWM power variations with different PMD values. It agrees well with measured FWM data in Fig. 2. For high PMD (> 10 ps), the period is quite narrow. Thus the nonlinear Poincare sphere method can measure PMD without scanning measurement signals in a wide optical bandwidth.

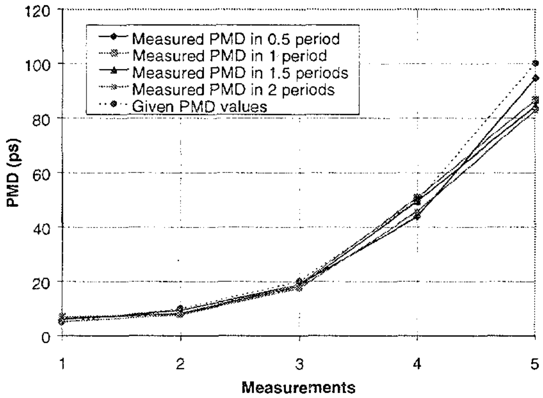

Fig. 3 Measured mean PMD and the given PMD.

Table 1 The wavelength width of one period of FWM power variations for different PMD values

PMD (ps)	5	10	20	50	100
Wavelength width (nm) per FWM period	1.6	0.8	0.4	0.16	0.08

IV. Conclusion and discussion

In summary, we have presented a new Poincare sphere method for measuring PMD by using FWM generation in single-mode optical fiber. It is based on the FWM power transfer function vs. the polarization states of the pump signals. Compared to the traditional Poincare sphere method, this method does not require measurement of the Stokes vectors and is less insensitive to mechanical vibration of measurement apparatus. Compared to the nonlinear fixed polarization analyzer method, this method does not need to scan a wide optical bandwidth and thus has fewer requirements on the measurement fiber.

Similar to the nonlinear method in [4], this technique may also be used as an in situ PMD measurement or monitoring method on dense wavelength-division multiplexed (DWM), traffic-carrying fibers. If the polarization states of the transmitted signals are fixed, the FWM products in the measurement fiber generated by wavelength channels may provide an estimate of the PMD. This can be done either span-by-span or over several spans.

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