Optical Engineering 46(3), 035007 (March 2007)

Measurement of polarization mode dispersion vectors in optical fibers using a virtual Mueller matrix method

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Abstract. A virtual Mueller matrix method is proposed to measure the first- and second-order polarization mode dispersion (PMD) vectors in optical fibers. This method not only can use a large frequency step to attain low-noise PMD vector data, but also does not require knowledge of the input polarization states. Our measurement method has a simpler setup and is more accurate than the traditional Mueller matrix method. [DOI: 10.1117/1.2714519]

Subject terms: polarization mode dispersion; polarization mode dispersion vector; Mueller matrix.

Paper 060475R received Jun. 16, 2006; revised manuscript received Sep. 10, 2006; accepted for publication Sep. 14, 2006; published online Mar. 15, 2007.

1 Introduction

According to the principal-state theory by C. D. Poole, polarization mode dispersion (PMD) is completely described by the PMD vector $\mathbf{\Omega}(\omega)$ in optical fibers without polarization-dependent loss or gain (PDL/G).[1,2] Up to now, PMD vector measurement methods in the frequency domain have been divided into two categories: those in the first are based on the equation deduced from $d\mathbf{S}/d\omega=\mathbf{\Omega}\times \mathrm{S}$, which involves derivatives of polarization states with respect to optical frequency,[2] and those in the second are based on the analysis of the transmission matrix, including the Jones matrix eigenanalysis (JME) method[3] and the Mueller matrix method (MMM).[4] The measurement methods in the first category do not require the knowledge of input polarization states, so only a polarization controller (PC) is employed to change the input polarization states. However, these measurement methods suffer from high noise due to high-precision demand in setting up frequencies with a very small step size as required by the differentiation. In the second category, the MMM has been demonstrated to be a good technique to attain low-noise high-resolution PMD data. The MMM can also measure the second-order PMD vector by employing the interleaving technique.[4] The advantages of the MMM include that it only requires two launches of input polarization states (in contrast with the JME method), and that it avoids the inaccuracies caused by the small differences of optical frequencies and Stokes vectors (in contrast with the measurement methods in the first category).[4] The disadvantage of the MMM is that it requires knowledge of the input polarization states. That is, in a traditional MMM measurement, the two input polarization states are required to be linearly polarized, and one of them should be parallel to the x axis of the chosen coordinate system.[4] (In principle, two nonparallel input polarization states are sufficient to determine the Mueller matrix, but they also have to be known in advance.) So a rotatable polarizer or a polarization-state generator has to be inserted in the measurement system, which increases the system complexity and also tends to induce errors in setting the predefined input polarization states.

In this paper, a virtual MMM (VMMM) is proposed. This technique does not require knowledge of the input polarization states, which simplifies the system setup and improves the measurement accuracy. Experimental results confirm the validity of the VMMM.

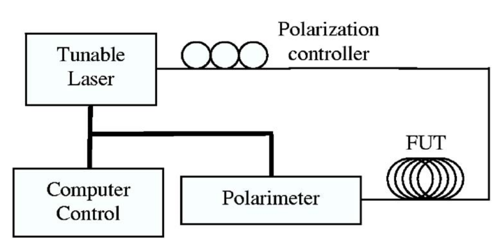

Fig. 1 Experimental setup for PMD vectors measurement in optical fibers.

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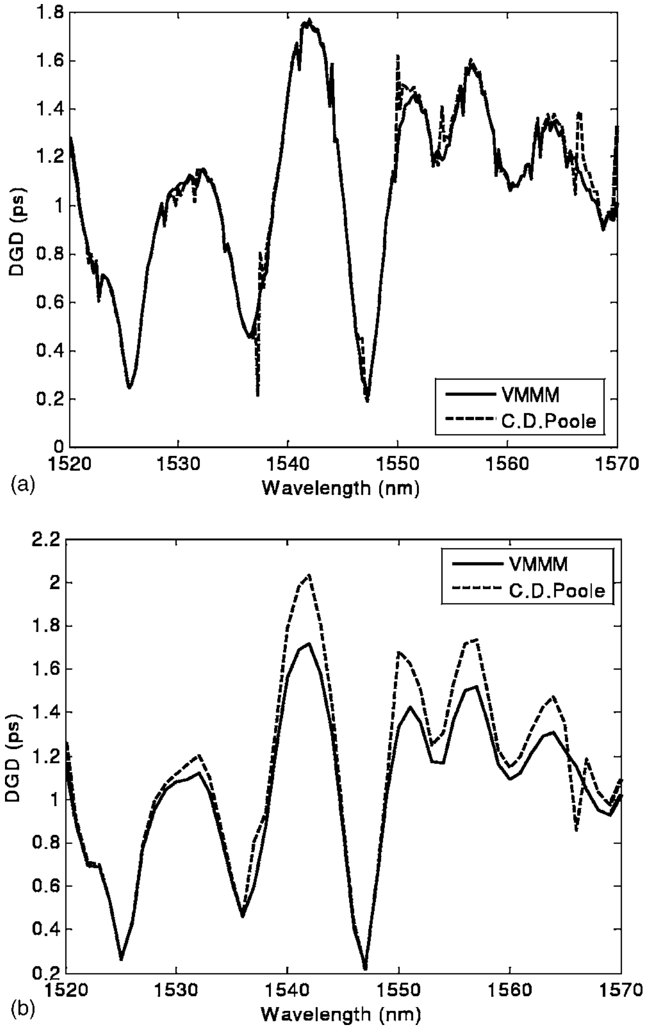

Fig. 2 DGD values measured by using VMMM and Poole's equation with two wavelength differences: (a) $\Delta\lambda = 0.25$ nm, (b) $\Delta\lambda = 1$ nm.

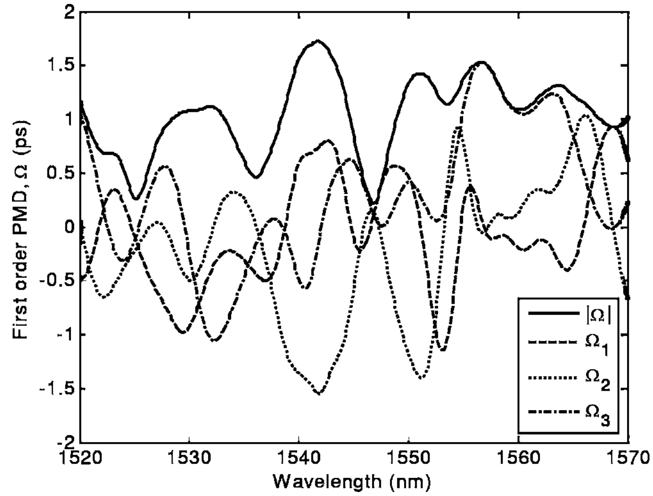

Fig. 3 Measured first-order PMD magnitude (solid curve) and its vector components (dashed curves).

2 Virtual Mueller Matrix Method

If the input polarization state $\mathbf{S}_{in}$ is fixed and the optical frequency is being swept, then at the output end of an optical fiber the output-normalized Stokes vectors at two adjacent frequencies are related by[4]

$$\mathbf{S}_{out}(\omega+\Delta\omega) = \mathbf{M}(\omega+\Delta\omega)\mathbf{M}^{-1}(\omega)\mathbf{S}_{out}(\omega). \tag{1}$$

Here $\mathbf{M}$ denotes the Mueller matrix. In fact, it is the matrix $\mathbf{M}_{\Delta}(\omega)=\mathbf{M}(\omega+\Delta\omega)\mathbf{M}^{-1}(\omega)$ that contains the information about the PMD vector.[4] In the MMM, the Mueller matrices at two adjacent frequencies are required to be measured first in order to obtain $\mathbf{M}_{\Delta}(\omega)$. This is the step that needs the knowledge of the input polarization states. Based on Eq. (1), if we consider $\mathbf{M}_{\Delta}(\omega)$ as the transmission matrix of a virtual optical system, with $\mathbf{S}_{out}(\omega)$ the input polarization state and $\mathbf{S}_{out}(\omega+\Delta\omega)$ the corresponding output polarization state, then $\mathbf{M}_{\Delta}(\omega)$ can be determined from $\mathbf{S}_{out}(\omega)$ and $\mathbf{S}_{out}(\omega+\Delta\omega)$ directly. The knowledge of $\mathbf{S}_{in}$ is hence not required at all.

Since the Mueller matrix $\mathbf{M}$ in an optical fiber with pure birefringence is orthogonal,[4] $\mathbf{M}_{\Delta}(\omega)$ is also an orthogonal matrix according to the matrix laws.[5] Therefore the problem under investigation becomes how to determine an orthogonal matrix $\mathbf{M}_{\Delta}(\omega)$ using arbitrary input states. For two fixed but unknown input polarization states $\mathbf{S}_{in}$ and $\mathbf{T}_{in}$, their corresponding outputs at frequencies ω and $\omega+\Delta\omega$ can be measured and related as $\mathbf{S}_{out}(\omega+\Delta\omega) = \mathbf{M}_{\Delta}(\omega)\mathbf{S}_{out}(\omega)$ and $\mathbf{T}_{out}(\omega+\Delta\omega)=\mathbf{M}_{\Delta}(\omega)\mathbf{T}_{out}(\omega)$. We can solve the two equations directly to determine $\mathbf{M}_{\Delta}(\omega)$ with the assistance of $\mathbf{M}_{\Delta}^{-1}=\mathbf{M}_{\Delta}^{T}$.[5] However, that technique is tedious, for some of the equations are nonlinear.

We propose instead an unconventional way of solving for $\mathbf{M}_{\Delta}(\omega)$. We assume there are three polarization states $\mathbf{U}_{1out}(\omega)=(1\ 0\ 0)^{T}$, $\mathbf{U}_{2out}(\omega)=(0\ 1\ 0)^{T}$, and $\mathbf{U}_{3out}(\omega) =(0\ 0\ 1)^{T}$ at frequency ω. If we can calculate their corresponding outputs $\mathbf{U}_{1out}(\omega+\Delta\omega)$, $\mathbf{U}_{2out}(\omega+\Delta\omega)$, and $\mathbf{U}_{3out}(\omega+\Delta\omega)$ at frequency $\omega+\Delta\omega$ from the measured data on $\mathbf{S}_{out}(\omega)$, $\mathbf{S}_{out}(\omega+\Delta\omega)$, $\mathbf{T}_{out}(\omega)$, and $\mathbf{T}_{out}(\omega+\Delta\omega)$, then $\mathbf{M}_{\Delta}(\omega)$ can be easily determined. In fact, because $\mathbf{M}_{\Delta}(\omega)$ is orthogonal, we have

$$\mathbf{S}_{out}(\omega+\Delta\omega)\cdot\mathbf{U}_{jout}(\omega+\Delta\omega) = \mathbf{S}_{out}(\omega)\cdot\mathbf{U}_{jout}(\omega),$$

$$\mathbf{T}_{out}(\omega+\Delta\omega)\cdot\mathbf{U}_{jout}(\omega+\Delta\omega) = \mathbf{T}_{out}(\omega)\cdot\mathbf{U}_{jout}(\omega),$$

$$[\mathbf{S}_{out}(\omega+\Delta\omega)\times\mathbf{T}_{out}(\omega+\Delta\omega)]\cdot\mathbf{U}_{jout}(\omega+\Delta\omega) = [\mathbf{S}_{out}(\omega) \times\mathbf{T}_{out}(\omega)]\cdot\mathbf{U}_{jout}(\omega). \tag{2}$$

Here $j=1,2,3$. Then the $\mathbf{U}_{jout}(\omega+\Delta\omega)$ can be calculated from Eq. (2) one by one as long as $\mathbf{S}_{out}(\omega+\Delta\omega)$ and $\mathbf{T}_{out}(\omega+\Delta\omega)$ are not parallel or antiparallel, which can be guaranteed as long as $\mathbf{S}_{in}$ and $\mathbf{T}_{in}$ are not parallel or antiparallel. In particular, when $\mathbf{S}_{in}$ and $\mathbf{T}_{in}$ are orthogonal in Stokes space, the optimum accuracy can be achieved. Then $\mathbf{M}_{\Delta}(\omega)$ can be determined by two arbitrary but unknown input polarization states as

$$\mathbf{M}_{\Delta}(\omega) = (\mathbf{U}_{1\text{out}}(\omega + \Delta\omega) \quad \mathbf{U}_{2\text{out}}(\omega + \Delta\omega) \quad \mathbf{U}_{3\text{out}}(\omega + \Delta\omega)). \tag{3}$$

The first-order PMD vector can be extracted from $\mathbf{M}_{\Delta}(\omega)$ using Eqs. (6), (7), and (8) in Ref. 4. Because this method is based on the direct measurement of a Mueller-like matrix $\mathbf{M}_{\Delta}(\omega)$, we call it the virtual Mueller matrix method.

3 Experimental setup and results

To verify the VMMM, an experimental setup is established as shown in Fig. 1. A tunable laser source emits completely polarized light with stable polarization state in a large wavelength range. The manually controlled PC is used to generate two fixed but unknown input polarization states. In our experiment, although we cannot know the exact input polarization states, we can make two inputs close to orthogonal by tuning the PC to two precalibrated states. So a high accuracy can be achieved in our measurements. The polarimeter is used to measure the output polarization states at different optical frequencies. Both the tunable laser source and the polarimeter are controlled by a computer for data synchronization.

The fiber under test (FUT) is a 2-km highly nonlinear single-mode optical fiber. In our experiments, the wavelength sweeping range is from 1520 to 1570 nm with 0.25- and 1-nm step sizes. The differential group delay (DGD) is first calculated using both the VMMM and Poole's equation [Eq. (9) in Ref. 2] for comparison. DGD values calculated with different step sizes are shown in Fig. 2. It is clear that the VMMM can use a larger optical frequency difference to attain higher signal-to-noise ratio. Poole's equation will give the wrong results when the optical frequency difference is large.

The first- and second-order PMD vectors are plotted in Fig. 3 and Fig. 4, respectively. The plots include magnitude as well as three components of the PMD vectors. For calculating the second-order PMD vector, the interleaving technique is employed with a nominal wavelength difference of 0.1 nm.

From the measured data on Ω and Ω_{ω}, we have $\langle\Omega_{\omega}^2\rangle = 4.8890 \times 10^{-49}$ and $\langle\Omega^2\rangle^2/3 = 4.8716 \times 10^{-49}$, which satisfies the Foschini-Poole relation $\langle\Omega_{\omega}^2\rangle = \langle\Omega^2\rangle^2/3$ very well with a relative error of 0.36%.[6]

4 Conclusion

We have proposed a VMMM for enhanced measurement of PMD vectors. This technique is superior to the traditional MMM in that it does not require the knowledge of input polarization states. At the same time, like the traditional MMM, the VMMM can use a large frequency measurement step to attain low-noise and high-resolution PMD data. Experimental results confirm the high performance of the proposed method.

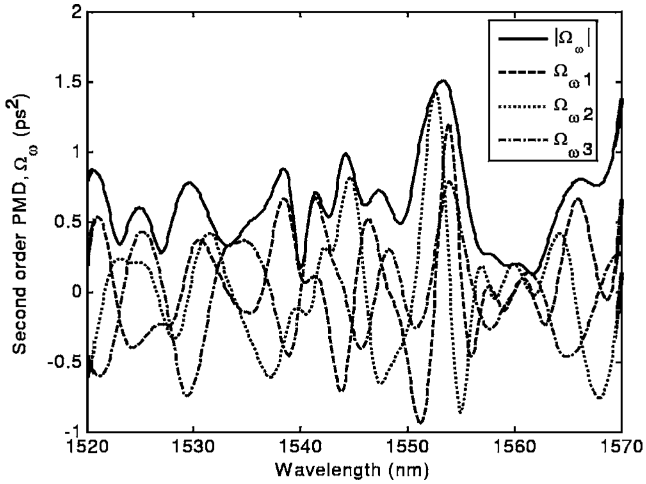

Fig. 4 Calculated second-order PMD magnitude (solid curve) and its vector components (dashed curves).

Acknowledgments

This work is partially supported by project 042 101 0015 of Agency for Science, Technology and Research (A*Star), Singapore, and the Open Fund of the Key Laboratory of Optical Communication and Lightwave Technologies, Beijing University of Posts and Telecommunications, Ministry of Education, China.

References

1. C. D. Poole and R. E. Wagner, "Phenomenological approach to polarization dispersion in long single-mode fibers," *Electron. Lett.* **22**(19), 1029–1030 (1986).
2. C. D. Poole, N. S. Bergano, R. E. Wagner, and H. J. Schulte, "Polarization dispersion and principal states in a 147-km undersea lightwave cable," *J. Lightwave Technol.* **6**(7), 1185–1190 (1988).
3. B. L. Heffner, "Automated measurement of polarization mode dispersion using Jones matrix eigenanalysis," *IEEE Photonics Technol. Lett.* **4**(9), 1066–1069 (1992).
4. R. M. Jopson, L. E. Nelson, and H. Kogelnik, "Measurement of second-order polarization-mode dispersion vectors in optical fibers," *IEEE Photonics Technol. Lett.* **11**(9), 1153–1155 (1999).
5. C. D. Meyer, *Matrix Analysis and Applied Linear Algebra*, Society for Industrial and Applied Mathematics, Philadelphia (2001).
6. G. J. Foschini and C. D. Poole, "Statistical theory of polarization dispersion in single mode fibers," *J. Lightwave Technol.* **9**(11), 1439–1456 (1991).

Biographies and photographs of the authors not available.