Precise evaluation of polarization mode dispersion by separation of even- and odd-order effects in quantum interferometry

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Abstract: The use of quantum correlations between photons to separate measure even- and odd-order components of polarization mode dispersion (PMD) and chromatic dispersion in discrete optical elements is investigated. Two types of apparatus are discussed which use coincidence counting of entangled photon pairs to allow sub-femtosecond resolution for measurement of both PMD and chromatic dispersion. Group delays can be measured with a resolution of order 0.1 fs, whereas attosecond resolution can be achieved for phase delays.

OCIS codes: (260.2030) Dispersion; (120.3180) Interferometry; (270.0270) Quantum Optics.

References and links

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1. Introduction: Dispersion Measurement - Classical versus Quantum

As optical communication networks migrate towards higher 40 Gbps and 100 Gbps data rates, system impairments due to dispersion, especially polarization mode dispersion (PMD), become a primary issue. This includes not only fiber PMD, but also contributions from switches, amplifiers, and all other components in the optical path. The fiber PMD and component PMD tend to accumulate in different manners as the size of the network grows. In the long length regime, the differential group delay (DGD) due to fiber PMD has a known dependance on length, growing as $\sqrt{L}$ [1]. In a similar manner, contributions from chromatic dispersion increase linearly in L. This known length dependence makes the dispersion of the optical fibers themselves relatively straightforward to measure and to take into account.

In contrast, component PMD was until recently considered to be too small in comparison to fiber PMD to affect significant penalties at the system level. Since the introduction of reconfigurable add-drop multiplexers (ROADMs), the number of components that could potentially contribute to the PMD in a given system has increased significantly. Although the dispersive contribution of each separate component is relatively small, together they are capable of accumulating and of thereby making a significant contribution to the total system impairment. It is therefore important to be able to precisely and efficiently measure small values of DGD. However, since only fiber PMD was important in the past, no measuring techniques were developed for efficient evaluation of small DGD values. With component PMD starting to play a significant role, developing high-resolution evaluation of small PMD values in a single optical switch or other small discrete optical component represents a new challenge to optical researchers that must be addressed by modern optical metrology. In this paper, we address the measurement of dispersive effects in such discrete elements.

Polarization mode dispersion is the difference between wavenumbers of two orthogonal states of light at fixed wavelength, or equivalently, a polarization-dependent variation of a material's index of refraction. A number of methods have been developed for measuring it [2, 3, 4, 5, 6, 7, 8, 9]. Many traditional techniques for measuring PMD rely on an interferometric approach for high-resolution measurements of absolute values of optical delays. This approach requires one to use a monochromatic laser source and to keep track of the number of interference fringes. Therefore, the accuracy of the approach is limited by the stability of the interferometer, by the signal-to-noise level of the detector, and by the wavelength of the monochromatic radiation, leading to significant limitations. For example, the use of monochromatic classical polarized light does not allow one to measure the relative delay between two orthogonally polarized waves in a single measurement, so several measurements at different frequencies must be used to reconstruct the polarization dispersion properties of materials. The use of highly monochromatic laser sources creates the additional problem of multiple reflections and strong irregular interference that may have detrimental effect on measuring polarization dispersion.

White-light or low-coherence interferometry [8] is another widely used approach. The ultimate resolution of such interferometric measurements will depend on the spectral bandwidth of the light source. Achieving sub-fs resolution in PMD measurement dictates the use of light sources with bandwidth in excess of 200 nm. Generating light of such a bandwidth with a smooth spectral profile is not an easy task in itself. Spectral modulations from existing sources with bumpy spectra produce 'ghost' features during measurement, leading to complications in dispersion evaluation. In addition, the visibility of interference with such super-broadband light

is diminished due to dispersion effects.

Overall, while classical techniques can provide high-resolution measurement of polarization mode dispersion they still have limitations in many areas that quantum-based techniques can address. For example, entangled photon states intrinsically provide an absolute value for polarization optical delay, in contrast to the conventional (classical) case, which is limited to determination of delay modulo an integer number of cycles of the light. This is mainly due to the fact that quantum interferometry exploits both phase and group velocity effects in the same measurement [10, 11], a feat not possible in classical optics.

The current practical resolution of conventional dispersion evaluation techniques is limited to a few femtoseconds (fs). The primary goal here is to use an interferometric setup with an entangled photon source to measure the component PMD of a small, discrete optical element to sub-femtosecond precision. Ideally, it would be desirable to measure chromatic dispersion with the same device, while allowing for the polarization and chromatic effects to be easily separable. We will show that this is indeed possible. Due to the frequency-anticorrelation in the entangled downconversion source used as illumination, we may independently determine the even-order and odd-order parts of the PMD's frequency dependence. Due to the reliance on the frequency anticorrelations within pairs of photons, the separation method is intrinsically a two-photon quantum effect, and is not present in the classical interferometer.

Classical attempts to simulate this even-odd separation effect by symmetrical chirping and anti-chirping of femtosecond laser pulses are constrained to a very narrow size of wavepacket thus making it not very practical. The availability of such a separation is useful in a number of circumstances. One example is when there is enough pulse broadening (second-order dispersion) to make accurate measurement of group velocity (first order dispersion) difficult. In a fiber, group velocity and broadening effects can be separated to some extent by simply taking a sufficiently long length of fiber as sample; the longer the fiber, the more accurately each can be measured. When dealing with switching elements or other small discrete optical elements, this option is not available. Another means must be found to prevent accurate measurement of the first-order group delay from being obscured by second-order broadening effects. That is what is accomplished here: the location of a dip in the coincidence rate may be used to find the group velocity, and this location is unaffected by the second-order broadening as a result of the even-order dispersion cancellation. Conversely, although the amount of broadening in a single small component may seem negligible, the total broadening from many such components present in a large network may be significant; thus high-accuracy measurements of these very small second-order dispersive contributions is important. Separating them off from the generally larger first-order contributions makes accurate measurements much easier.

We note that since the component being analyzed is assumed to be relatively small, the principal polarization axes may be assumed to remain constant over the longitudinal length of the object and to be independent of frequency, with the dispersive contributions of the two polarization components remaining independent of each other. This greatly simplifies the analysis.

After a review of background and notation in section 2, three measurement methods will be discussed in sections 3-5. The apparatus of section 3 uses a single detector to make a classical measurement; the system is illuminated with a broadband classical light source. In contrast, quantum measurements are made using two detectors connected in coincidence with illumination provided by a source of entangled photon pairs (spontaneous parametric downconversion, (SPDC)). We will examine two quantum measurement setups in sections 4 and 5. In addition, in section 5 we give a qualitative analysis that allows the positions of dips (or peaks) independently of the mathematical formalism.

The two quantum configurations will be distinguished from each other by referring to them as type A or type B. They differ only in the presence or absence of a final beam splitter before

detection, so they may both be implemented in a single apparatus by allowing a beam splitter to be switched in or out of the optical path. Similarly, by adding an additional polarizer and counting the singles rate at one detector instead of coincidence events, the classical setup may also be implemented in the same device. Thus, a single apparatus could be made which is capable of performing any of the three types of measurements to be discussed.

This paper builds on two previous lines of work. The apparatus used for the type A setup was introduced previously [10, 11], where it was shown that quantum interferometry can achieve higher resolution than classical methods in measurements of PMD. Separately, the segregation of even- and odd-order chromatic dispersion effects was demonstrated in [14]. Here, we bring the two strands together in a single device (type B), showing that we can separate even- and odd-order effects in PMD, as well as in chromatic dispersion, and that we can do so with the resolution available to the type A device.

As a further benefit of the quantum devices over classical methods, note that for the quantum cases there is no need to know in advance the principal axis directions of the device or object being measured. Although the incoming photons are aligned along particular axes that are linked to a birefringent crystal orientation, their projections onto any rotated pair of orthogonal axes (including the principle axes of the sample) will remain equally entangled, allowing the method to work without any need to align the axes of the source and the device under test.

2. Chromatic Dispersion and Polarization Mode Dispersion

First consider a material for which the index of refraction is independent of polarization. The frequency dependence of the wavenumber $k = \frac{2\pi n(\lambda)}{\lambda}$ is given by a dispersion relation, which can be written near some central frequency Ω_0 as

$$k(\Omega_0 \pm \omega) = k_0 \pm \alpha\omega + \beta\omega^2 \pm \gamma\omega^3 + \ldots \tag{1}$$

for $|\omega| << \Omega_0$. The coefficients $\alpha, \beta, \ldots$ characterize the *chromatic dispersion* or variation of the refractive index with frequency. Explicitly,

$$k_0 = k(\Omega_0), \qquad \alpha = \left.\frac{dk(\omega')}{d\omega'}\right|_{\omega'=\Omega_0}, \tag{2}$$

$$\beta = \left.\frac{1}{2!}\frac{d^2k(\omega')}{d\omega'^2}\right|_{\omega'=\Omega_0}, \qquad \gamma = \left.\frac{1}{3!}\frac{d^3k(\omega')}{d\omega'^3}\right|_{\omega'=\Omega_0}, \ldots \tag{3}$$

Rather than looking at the individual terms in the expansion (1), we may also collect together all terms containing even powers of ω and all terms containing odd powers to arrive at an expansion containing only two terms:

$$k(\Omega_0 + \omega) = k_{even}(\omega) + k_{odd}(\omega), \tag{4}$$

where

$$k_{even}(\omega) = k_0 + \beta\omega^2 + \mathcal{O}(\omega^4), \tag{5}$$

and

$$k_{odd}(\omega) = \alpha\omega + \gamma\omega^3 + \mathcal{O}(\omega^5). \tag{6}$$

In the case of nonzero *polarization mode dispersion* (PMD), the index of refraction varies with polarization. We now have two copies of the dispersion relation, one for each independent polarization state:

$$k_H(\Omega_0 \pm \omega) = k_{H0} \pm \alpha_H\omega + \beta_H\omega^2 + \ldots \tag{7}$$

$$= k_{H,even}(\omega) + k_{H,odd}(\omega) \quad (8)$$

$$k_V(\Omega_0 \pm \omega) = k_{V0} \pm \alpha_V \omega + \beta_V \omega^2 + \ldots \quad (9)$$

$$= k_{V,even}(\omega) + k_{V,odd}(\omega), \quad (10)$$

where H, V denote horizontal and vertical polarization.

To describe the PMD, we must define quantities that measure the differences between the two polarization states:

$$\Delta k_0 = k_{V0} - k_{H0}, \qquad \Delta\alpha = \alpha_V - \alpha_H, \qquad \Delta\beta = \beta_V - \beta_H. \quad (11)$$

These parameters are defined per unit length. For the case of primary interest to us, discrete fixed-size objects, the formulas should really be written in terms of the relevant lumped quantities

$$\Delta\phi \equiv l\Delta k_0, \qquad \Delta A \equiv l\Delta\alpha, \qquad \Delta B \equiv l\Delta\beta, \quad (12)$$

where l is the axial thickness of the device under study. However, we will continue to use the α, β, and Δk_0 parameters of eq. 11, both because they are more commonly used, and because they allow easy comparison to the formulas used in fiber optics.

Note that $\Delta k_0 = \frac{\Omega_0 \Delta n(\Omega_0)}{c}$ is a measure of the difference in phase velocity between the two polarization modes, while $\Delta\alpha$ and $\Delta\beta$ are related to the difference in group velocity. Also, it should be pointed out that the PMD and the chromatic dispersion are not entirely independent effects; in particular, the PMD coefficients themselves (Δk_0, $\Delta\alpha$, $\Delta\beta$) are frequency dependent.

In the quantum cases, it is convenient to also define $\tau_- = DL$, where L is the thickness of the nonlinear downconversion crystal and $D = u_0^{-1} - u_e^{-1}$ is the difference of the group velocities of the two polarizations inside the crystal. We will restrict ourself to the simplest case of a bulk crystal, so the spectral distribution of the downconverted pairs is described by the function [12, 13]

$$\Phi(\omega) = \mathrm{sinc}\left(\frac{1}{2}\tau_- \omega\right), \quad (13)$$

where the sinc function is defined by $\mathrm{sinc}(x) = \frac{\sin(x)}{x}$. Photons are emitted from the downconversion process in frequency- anticorrelated pairs: the frequencies $\Omega_0 \pm \omega$ in each pair are shifted equally, but in opposite directions, from the central frequency $\Omega_0 = \omega_{pump}/2$, with the distribution of frequency shifts ω being given by $\Phi(\omega)$ of eq. 13. The downconversion time scale, τ_-, is inversely proportional to the spectral width of the source, and therefore determines the precision of the resulting measurements. The spectrum may be made wider by using a thinner nonlinear crystal, but this occurs at the expense of reducing the intensity of the downconverted light. High intensity and large bandwidth may be obtained simultaneously by use of a chirped crystal, although some of the details of the following analysis will then be changed.

3. Classical PMD Measurement

An apparatus equivalent to that shown schematically in fig. 1 [8] is commonly used to measure polarization mode dispersion. The illumination may be provided by any sufficiently broadband light source. For easier comparison with the later sections, we will assume the illumination is provided by type II parametric downconversion, but this is not necessary; since we use a single detector, the entanglement of the downconverted photons will play no role.

Assume an arbitrary amount of H and V polarization out of the downconversion crystal, so that the incident field in Jones vector notation is proportional to

$$\int \begin{pmatrix} A_H(\omega) \\ A_V(\omega) \end{pmatrix} d\omega, \quad (14)$$

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