Modulation phase-shift measurement of PMD using only four launched polarisation states: a new algorithm

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A new algorithm is presented for measuring differential group delay in optical fibres and components using the modulation phase-shift technique which only requires the launching of four polarisation states. This significantly improves the previous technique that requires polarisation scanning. Experimental results demonstrate good agreement between these two methods.

Introduction: The modulation phase-shift (MPS) technique of measuring polarisation-mode dispersion (PMD) is useful for very narrow bandwidth (< 0.05nm) measurements of differential group delay (DGD) [1]. However, the current implementation of MPS involves the cumbersome process of random polarisation scanning, which drastically reduces the measurement speed and increases the possibility of errors due to group delay drift. In this letter a closed-form algorithm is introduced for use with the MPS apparatus in which DGD is measured by launching only four predetermined polarisation states. These states must form a 'Mueller set', i.e. three of the states must lie on a great circle of the Poincaré sphere and are separated by 90° (Poincaré sphere co-ordinates) and the fourth state lies on the axis of that great circle.

Description: A typical MPS system is shown in Fig. 1. A polarised RF-modulated laser beam passes through a polarisation controller. The light is transmitted through the test device and impinges on a phase sensitive detector that measures the RF phase delay between the detected signal and an electrical reference from the oscillator. In the typical polarisation scanning measurement technique, the input polarisation state is randomised over all possible states while the RF phase delay is recorded for each launch. The minimum and maximum RF phase delays correspond to light launched along (or near) the fast and slow principal axes of the device, and their difference is proportional to the DGD. The accuracy of this technique depends on how close a launched state comes to each principal state of polarisation (PSP). In contrast, in the four-point technique described here, the DGD is measured by launching only four states with no requirement of alignment with the PSPs.

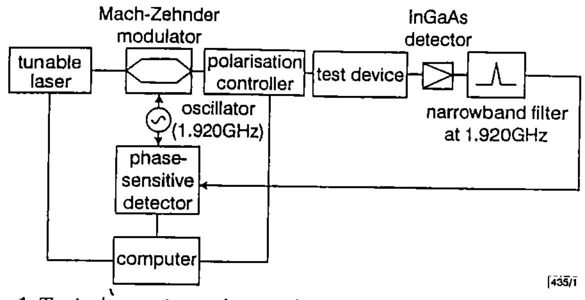

Fig. 1 *Typical experimental setup for modulation phase-shift measurement of differential group delay*

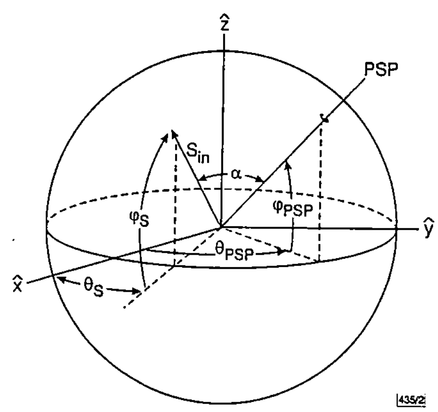

Fig. 2 *Poincaré sphere diagram showing geometry of measurement*

PSP is principal state of polarisation for device under test, and S_{in} is generalised input state of polarisation

Theory: Consider the RF phase delay for an arbitrary polarisation state. When light of intensity I_0 is launched with a polarisation state that makes an angle α (Poincaré sphere co-ordinates) with one of the device's PSPs, the light will be divided into its two projections on the fast and slow principal axes. The intensities of these projections are $I_+ = I_0\cos^2(\alpha/2)$ and $I_- = I_0\sin^2(\alpha/2)$, and the RF phase delays accumulated by I_+ and I_- at the exit of the device will be $\Phi + \delta_{RF}$ and $\Phi - \delta_{RF}$, respectively. The polarisation-independent phase offset Φ is due to both the system's mean group delay and electronic delays. δ_{RF} is the polarisation-dependent part which is due to PMD. Previously, polarisation scanning has been the only way to explicitly measure Φ and δ_{RF} for an unknown PSP orientation. However, a small amount of mathematical analysis can be used to illustrate how the phase delays from four different polarisation states will yield both Φ and δ_{RF}. The phase detector yields the phase resulting from the sum of the signals $I_+ + I_-$, which can be shown (by phasor analysis) to be

$$\phi_{RF} = \tan^{-1}\left(\cos\alpha \tan\frac{\delta_{RF}}{2}\right) + \Phi \qquad (1)$$

Of course, for an arbitrary test device, the PSP axes and α are unknown. Using the angles defined in Fig. 2, and assuming that the input polarisation state S_{in} is confined to the equator of the sphere ($\varphi_{in} = 0$), α is given as

$$\alpha = \cos^{-1}(\cos\varphi_{PSP}\cos(\theta_{PSP} - \theta_S)) \quad (2)$$

Substituting this into eqn. 1 gives

$$\phi_{RF} = \tan^{-1}\left(\cos\varphi_{PSP}\cos(\theta_{PSP} - \theta_S)\tan\frac{\delta_{RF}}{2}\right) + \Phi \quad (3)$$

δ_{RF} can be determined from phase measurements for four different launch polarisation states. The simplest solution is a Mueller set of four polarisation states that are separated from each other by 90° on the Poincaré sphere, but have no preferred absolute orientation with respect to the PSP. For the co-ordinate system of Fig. 2, four such states are: $S_A = (\theta_S = 0, \varphi_S = 0)$; $S_B = (\theta_S = 90°, \varphi_S = 0)$; $S_C = (\theta_S = 180°, \varphi_S = 0)$; $S_D = (\varphi_S = 90°)$. Substituting the first three co-ordinates into eqn. 3 gives the measured RF phases for S_A, S_B and S_C, respectively:

$$\phi_{RF,A} = \tan^{-1}\left(\cos\varphi_{PSP}\cos\theta_{PSP}\tan\frac{\delta_{RF}}{2}\right) + \Phi \quad (4)$$

$$\phi_{RF,B} = \tan^{-1}\left(\cos\varphi_{PSP}\sin\theta_{PSP}\tan\frac{\delta_{RF}}{2}\right) + \Phi \quad (5)$$

and

$$\phi_{RF,C} = -\tan^{-1}\left(\cos\varphi_{PSP}\cos\theta_{PSP}\tan\frac{\delta_{RF}}{2}\right) + \Phi \quad (6)$$

Since S_D is not on the equator, eqn. 2 does not apply. However, this special case has $\alpha = \pi/2 - \varphi_{PSP}$, so we use eqn. 1 directly to find

$$\phi_{RF,D} = \tan^{-1}\left(\sin\varphi_{PSP}\tan\frac{\delta_{RF}}{2}\right) + \Phi \quad (7)$$

S_A and S_C are orthogonal polarisation states, and so the average of their measured RF phases gives the polarisation independent phase offset

$$\phi_{RF} = (\phi_{RF,A} + \phi_{RF,C})/2 \quad (8)$$

Subtracting this phase offset from the measured phases of states S_A, S_B, and S_D allows the RF retardance δ_{RF} to be calculated as

$$\delta_{RF} = 2\tan^{-1}\left[\left(\tan^2(\phi_{RF,A} - \Phi) + \tan^2(\phi_{RF,B} - \Phi) + \tan^2(\phi_{RF,D} - \Phi)\right)^{1/2}\right] \quad (9)$$

This RF retardance converts into the DGD at the measurement wavelength as

$$\Delta\tau = \frac{\delta_{RF}}{2\pi}\frac{1}{f} \quad (10)$$

where f is the RF modulation frequency (δ_{RF} is in radians). So, by measuring the RF phase delay at any four Mueller set points as defined above, eqns. 9 and 10 will yield the DGD.

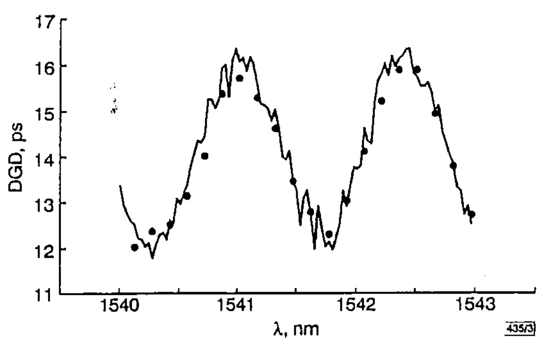

Fig. 3 *Experimental comparison of wavelength dependent differential group delay measurements using modulation phase-shift with polarisation scanning and four-point technique*

● polarisation scanning
——— four-point technique

Results and discussion: The system of Fig. 1 was used to verify this four-point algorithm. The vector voltmeter used for RF phase detection has a phase resolution of 0.1°, giving a 0.15ps temporal resolution at the 1.92GHz modulation frequency. The test device consisted of three (~6m length) sections of polarisation-maintaining fibre (PMF) connected together at random angles. The DGD was measured as a function of wavelength over a 3nm range using both MPS implementations (polarisation scanning and the four-point method) simultaneously. The results are shown in Fig. 3.

In the four-point technique, one circular and three linear states, horizontal, vertical and '45°' (equal amounts of horizontal and vertical), were launched at each wavelength, and the DGD was measured via eqns. 9 and 10. The phase of the vector voltmeter was read five times at each polarisation state to reduce random noise. The polarisation scanning measurement involved 300 random polarisation state launches (five phase measurements per launched state) per DGD point. The angle between the PSP and the closest launched state gives a measure of the absolute error incurred in the measurement (always negative). Assuming that the 300 launched polarisation states are uniformly distributed about the Poincaré sphere, then on average we expect at least one launch point to be no farther than 6° from the PSP. Substituting 6° for α in eqn. 1 shows that this sampling density will yield a systematic uncertainty in DGD of < 0.5% due to the polarisation scanning implementation.

The agreement between the polarisation scanning and the four-point implementations is very good. On average, the four-point technique yielded values which were ~1% higher than the polarisation scanning technique. The sign of this disagreement agrees with the finite sampling bias described above. However, the magnitude is larger than expected. Random noise (much larger than the 0.15ps phase uncertainty) is also seen in the four-point measurement. This is probably due to temperature-induced changes in the group delay of the fibre during the course of the measurement. To reduce this effect as much as possible, the test fibre was held in an insulated, thermally stabilised chamber. But ~50cm of the fibre leads were outside the chamber and were exposed to slight temperature changes, < 1°C. The effects of this drift in group delay might be reduced by choosing a sampling order of launched states which has orthogonal states measured with a greater frequency.

Conclusion: Results from a Jones matrix eigenanalysis (JME) have already been shown to agree with the results from the polarisation scanning MPS technique [1]. Therefore, these latest results imply agreement between the four-point MPS method and JME as well. The simplification afforded by this four-point technique allows for a greater flexibility in the design of the MPS system. For example, the polarisation controller no longer needs to allow arbitrary access to the Poincaré sphere, but only to four fixed polarisation states. Combinations of polarisers and waveplates could be inserted in front of (or behind) the test device, or the output from the test device could be split and sent to four separate detectors each with a different polarising element in front. This four-point technique also allows simultaneous measurements of DGD and polarisation dependent loss (PDL), since PDL measurements can be made by measuring the output power from the same four states (Mueller set) [2].

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