

CHARACTERIZATION OF FEMTOSECOND FIRST- AND SECOND-ORDER PMD

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Abstract A novel Sagnac loop is implemented for measuring femtosecond first- and second-order PMD spectra. The results agree well with the measurements carried out with a new commercial Optical Vector Analyzer (OVA) made by Luna Technologies.

Introduction

PMD in fiber devices is caused by wavelength dependence of the birefringence and its orientation axes, or the associated PSPs. The use of a Sagnac loop for PMD measurement was first proposed in [1], but the method measures only the wavelength averaged PMD and thus cannot determine the PSPs and second-order PMD (SOPMD).

In this work, we implement a π -shifted Sagnac loop for characterization of femtosecond first- and SOPMD that is insensitive to the birefringence axes orientation of the device under test (DUT) [2]. PMD and PSPs spectra are measured and SOPMD is determined. The results agree well with the ones obtained by a novel commercial Optical Vector Analyzer (OVA) from Luna Technologies.

The Sagnac loop

Sagnac fibre loop is shown in Fig. 1 where the π -shift between the clockwise and counterclockwise beams is introduced by the HWP. Sagnac loop has been studied using Jones calculus [2, 3]. The electric-field components at the fibre coupler exit, E_{1n}^{out} in reflection arm 1 and E_{2n}^{out} in transmission arm 2, are:

$$\begin{aligned} E_{1n}^{out} &= K_n^{1/2}(1-K_n)^{1/2}J^a(\omega)E_{1n}^{in} + K_n^{1/2}(1-K_n)^{1/2}J^c(\omega)E_{1n}^{in} \\ E_{2n}^{out} &= K_nJ^a(\omega)E_{1n}^{in} + (1-K_n)J^c(\omega)E_{1n}^{in} \end{aligned} \quad (1)$$

where K_n is the splitting ratio, and n refers to the x- or y-component. $J^c(\omega)$ and $J^a(\omega)$ are clockwise and counterclockwise Jones matrices for the light propagating in the loop. The following matrices for the QWP and DUT were assumed in the calculations:

$$\begin{aligned} J_{HWP}^c &= \begin{pmatrix} i \cos 2\rho & i \sin 2\rho \\ i \sin 2\rho & -i \cos 2\rho \end{pmatrix}, \\ J_{DUT}^\delta &= \begin{pmatrix} e^{i\frac{\delta}{2} \cos^2 \alpha} + e^{-i\frac{\delta}{2} \sin^2 \alpha} & 2i \sin 2\alpha \sin \frac{\delta}{2} \\ 2i \sin 2\alpha \sin \frac{\delta}{2} & e^{-i\frac{\delta}{2} \cos^2 \alpha} + e^{i\frac{\delta}{2} \sin^2 \alpha} \end{pmatrix}, \end{aligned} \quad (2)$$

where ρ and α are orientation angles of the HWP and DUT birefringence axes, and δ is the DUT birefringence. For $K_n = 0.5$, transmission in arm 2 is:

$$T(\lambda) = \sin^2 \frac{\delta(\lambda)}{2} \sin^2 2\rho. \quad (3)$$

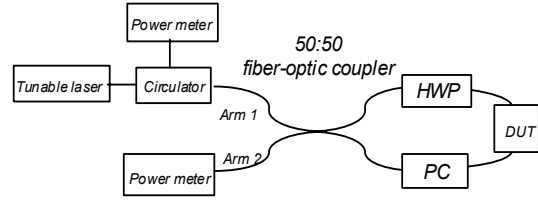


Fig. 1. π -shifted Sagnac interferometer.

Eq. (3) shows that the π -shifted Sagnac loop response is independent of the input polarization and the DUT birefringence axes orientation and for $\rho = 45^\circ$, it depends only on the DUT's birefringence. Hence, we can recover the DGD spectra through intensity scans as $DGD = d\delta(\omega)/d\omega$ with ω the optical frequency. Sagnac loop response with only DUT is:

$$T(\lambda) = \sin^2 \frac{\delta(\lambda)}{2} \sin^2 2\alpha. \quad (4)$$

The drawback of the conventional Sagnac loop is apparent from Eq. (4), namely the dependence on the DUT's orientation angle α . The DUT birefringence axes are determined by first measuring the DUT birefringence using our scheme (Eq. (3)), then measuring the corresponding $T(\lambda)$ without the HWP and calculating the angle α from Eq. (4). The second-order PMD components are calculated below.

Optical Frequency Domain Characterization (OFDC) Technique

The full complex characterization of transmission and reflection spectra of an NxN-port optical DUT by using the OFDC technique is described in [4]. The novel commercial instrument OVA made by Luna Technologies is based on this technique. To characterize a two-port device, the wavelength dependency of four parameters is measured in a fiber-optic network shown in Fig. 2. A two-port DUT can be considered as a four-port when measuring polarization effects which is accomplished by coupling polarization beamsplitters to both ports of the DUT. In this technique, a set of Jones matrices, $J_{DUT}(\omega_i)$, is the output from the Luna OVA measurement using a

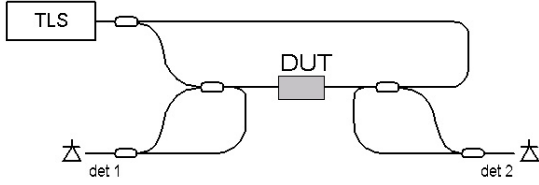


Fig. 2. Four parameter measurement schematics.

a single sweep tunable laser. DGD is calculated as [5]

$$\Delta\tau = \left| \frac{\text{Arg}(\rho_1 / \rho_2)}{\Delta\omega} \right| \quad (5)$$

where ρ_1 and ρ_2 are the eigenvalues of the matrix product $\left[\frac{d}{d\omega} J_{DUT}(\omega_2) \right] J_{DUT}^{-1}(\omega_1)$ with $J_{DUT}^{-1}(\omega_1)$ being the inverse Jones matrix and $\Delta\omega = \omega_2 - \omega_1$.

SOPMD representation

The PMD is described as the vector $\vec{\Omega}(\omega) = \Delta\hat{q}$ in Stokes space, e.g., [6] where $\Delta\tau$ is the DGD, and \hat{q} is a unit Stokes vector in the direction of the fast PSP. The SOPMD is the derivative

$$\frac{d\vec{\Omega}(\omega)}{d\omega} = \vec{\Omega}_{\omega}^{\text{parallel}} + \vec{\Omega}_{\omega}^{\text{perpend.}} = \frac{d\Delta\tau}{d\omega} \hat{q} + \Delta\tau \frac{d\hat{q}}{d\omega} \quad (6)$$

$\vec{\Omega}_{\omega}^{\text{parallel}}$ causes polarization dependent chromatic dispersion (PCD) and $\vec{\Omega}_{\omega}^{\text{perpend.}}$ is the rate of PSPs rotation which results in signal depolarization. The relationship between the PMD vector, $\vec{\Omega}(\omega)$, and the DUT's Jones matrix, $J_{DUT}(\omega)$, has been derived in [6].

$\delta(\omega) = \Delta\tau\Delta\omega + \frac{1}{2} \frac{d\Delta\tau}{d\omega} \Delta\omega^2$ is the frequency-dependent birefringence with $\Delta\omega$ the deviation from the carrier frequency ω . PCD is related to $|\vec{\Omega}_{\omega}^{\text{parallel}}|$ in Eq. (6) as:

$$PCD = \frac{d\Delta\tau}{d\lambda} = -\left(\frac{2\pi c}{\lambda^2} \right) \frac{d\Delta\tau}{d\omega} = -\left(\frac{2\pi c}{\lambda^2} \right) |\vec{\Omega}_{\omega}^{\text{parallel}}|. \quad (7)$$

$\alpha(\omega)$ is defined as $\alpha(\omega) = \alpha_0 + \frac{d\alpha(\omega)}{d\omega} \Delta\omega$, with α_0

the frequency-independent part and

$$\frac{d\alpha(\omega)}{d\omega} = k = \frac{1}{4} \left| \frac{d\hat{q}}{d\omega} \right|, \quad (8)$$

k in [ps] specifies the frequency-dependent rotation rate of the PSPs according to Eq. (6).

DGD and PSPs spectra and SOPMD

Measurements were carried out in the set-up shown in Fig. 1 with a fiber-optic coupler tested as the DUT. The calculated DGD from Eq. (3) from the intensity scans and the corresponding DGD from Luna OVA (Eq. (5)) are presented in Fig. 3. Figure 4 shows the SOPMD obtained with the Sagnac loop and Luna OVA as a vector sum of both components according to Eqs. (6)-(8). In this DUT, $|\vec{\Omega}_{\omega}^{\text{parallel}}|$ related to the

PCD was found to be dominant. Although the PSP rotation rate is not insignificant, $|\vec{\Omega}_{\omega}^{\text{perpend.}}|$ related to it from Eq. (8) was negligible compared to $|\vec{\Omega}_{\omega}^{\text{parallel}}|$.

PCD was dominant because of the well-defined birefringence axes in this DUT. As it can be seen from Figs. 3 and 4, there is a good agreement between the measurement methods.

Conclusions

We have implemented a π -shifted Sagnac loop for characterization of femtosecond first- and second-order PMD. The DGD and PSPs spectra are measured by combining the novel and conventional Sagnac loops. Thus the SOPMD is fully determined with the PCD and the frequency-dependent PSPs rotation. The results agree well with a novel commercial OVA for full characterization of PMD made by Luna Technologies.

References

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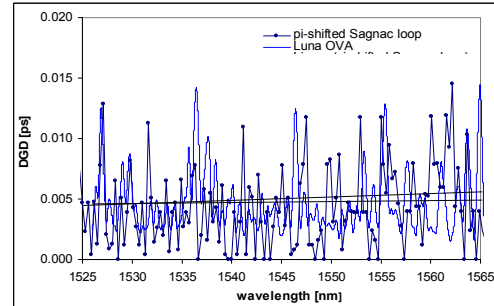


Fig. 3. DGD from the π -shifted Sagnac loop (dots) and Luna OVA (solid line).

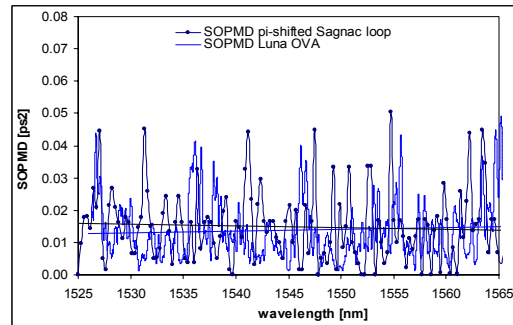


Fig. 4. SOPMD by combining conventional and π -shifted Sagnac loop (dots) and Luna OVA (solid line).