First and Second Order PMD Emulator

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Abstract: *We present a PMD emulator where the DGD and the ratio between first and second order PMD can be set by the user. Contrary to approaches which try to mimic a standard fiber as closely as possible, our emulator gives one (adjustable) value for the PMD[1]. This allows to directly determine the maximum (instantaneous) values for first and second order PMD for a given permissible system impairment.*

Introduction

Upgrading the existing telecom systems to high bit rates (≥10 Gb/s) leads to several problems. Already some time ago, the impact of first and second order PMD in such systems has been analyzed [1,2]. It was found that second order PMD, i.e. the frequency dependence of the Principle States Vector Ω (PSP), can lead to important fluctuations around the mean penalties induced by first-order PMD. For the case of large values of the chromatic dispersion, second order PMD becomes in fact a major source of performance degradation [1]. Moreover, with the advent of PMD compensators, which typically compensate for first order effects only (leaving higher orders unaffected or even increasing them), impairments due to accumulated 2nd order PMD are to be expected [3].

Consequently, second order PMD is an important issue for a proper assessment of system performance, and PMD emulators should therefore not only include the first, but also the 2nd order. The emulators of today have the strategy to mimic as closely as possible long standard fibers with polarization mode coupling. They typically consist of pieces of polarization maintaining (PM), highly birefringent fibers concatenated either by splicing or by rotatable connectors. In the first type, the desired Maxwellian pdf for the DGD is obtained by taking an ensemble over a large wavelength interval. However, the wavelength dependence of the PSP Ω is usually not accounted for in a correct way [4]. Using a fixed wavelength and changing the coupling among the PM fibers (e.g. by changing the temperature) to obtain a Maxwellian distributed DGD, there are indications that second order PMD could be quite well approximated [5]. The same holds for the second type of emulators, where the coupling is changed by mechanically varying the birefringence axes directions of the individual trunks. However, a large number of trunks (>15, [4,5]), and a large number of different realizations are to be used. This adds to the emulator complexity and measurement time.

We therefore opt for a different approach, where the user can set a constant value for the first and ratio of first to second order PMD, independent of the wavelength. Consequently, no statistics is reproduced as in the other emulators. However, the (instantaneous) PMD value is known precisely without having to measure it, and can be linked to the corresponding system penalty. The probability to be worse than that can then be obtained from the known PMD (DGD and 2nd order) statistics of long fibers (see e.g. the summary in [6]). In addition, our emulator allows to simulate situations - like a first order compensated system with low DGD and large 2nd order PMD - not achievable in emulators that mimic long standard fibers.

[1] in this letter, PMD mentioned with respect to our modulator explicitly includes both the value for the DGD ('mean' first order PMD) and the 'mean' second order PMD (with no difference existing between the values and their mean due to the absence of statistical fluctuations)

Principle of operation

The emulator is based on 2 trunks of PM fiber, with a coupling angle φ between their PSP. The overall PSP Ω then becomes [7]

$$\vec{\Omega}(\omega)=\tfrac{1}{2}\beta_2\vec{e}_2+\tfrac{1}{2}\beta_1(\vec{e}_1\cdot\vec{e}_2)\vec{e}_2+\tfrac{1}{2}\beta_1\cos(\beta_2\omega)(\vec{e}_1-(\vec{e}_1\cdot\vec{e}_2)\vec{e}_2)+\tfrac{1}{2}\beta_1\sin(\beta_2\omega)\vec{e}_1\times\vec{e}_2 \quad (1)$$

where $\vec{\Omega}_{1,2}=\beta_{1,2}\vec{e}_{1,2}$ are the PSP of the first and second trunk with DGDs of β_1 and β_2, respectively. Assuming that β_i and $\vec{e}_i$ are independent of wavelength (a very good approximation for PM fibers), one can straightforwardly calculate the amount of first and second order PMD,

$$\begin{aligned}&\left|\vec{\Omega}(\omega)\right|^2=\mathrm{DGD}^2=\beta_1^2+\beta_2^2+2\beta_1\beta_2\cos(\varphi)\\&\left|\frac{\partial}{\partial\omega}\vec{\Omega}(\omega)\right|=\left|\vec{\Omega}_\omega\right|=\beta_1\beta_2\sin(\varphi)\end{aligned}\quad (2)$$

As one can see, the overall DGD and amount of second order PMD are both constant with wavelength. The derivative of the modulus of $\vec{\Omega}$, which accounts for about $1/9^{th}$ of the total amount of second order PMD in a long standard fiber [2], is therefore zero, and the second order PMD vector $\vec{\Omega}_\omega$ becomes orthogonal to the PSP $\vec{\Omega}$.

Due to the dependence of the amount of first and second order PMD on the coupling angle φ (eq.2), one can set a desired ratio ξ of second to first order PMD as is shown in Fig.1 for two PM fibers having the same DGD. For long fibers, Foschini and Poole showed that $\xi=1/3$. Note that the ratio set by the angle φ, $\xi=(\tan(\varphi)/2)^2$, is conserved for any values of DGD, as long as they are the same for both fibers.

Fig.2 shows theoretical (eq.2) and measured amounts of first and second order PMD for different coupling ratios $\cos(\varphi)^2$ for 2 PM fibers with DGDs of 2 and 5.65 ps, respectively. The standard JME method was used to extract the PSP as a function of wavelength, where large angles could be used as the PSP is known to move regularly on a circle on the Poincaré Sphere in that specific situation. As the figure demonstrates, good agreement of the measurements (dots) and model (lines) was obtained.

Experimental realization and results

The experimental set-up for the emulator is shown in Fig.3. It is nothing else than the analog to two PM fibers with a coupling φ and adjustable DGD.

The parallel and orthogonal polarization mode of the input PM fiber are split at the first PBS, allowing to induce a retardation (0ps - 300ps) on the orthogonal mode using a free space delay line. The two modes are recombined at the second PBS, again with the axes of the following PM fiber aligned. The light trajectory up to the coupling φ^* therefore represents the first PM fiber, with DGD $\Delta\tau_1$. The polarization mode extinction ratio at the second PBS was measured to be ~22dB. The loss up to the coupling point φ^* was ~3dB for the lower arm and 1dB for the upper arm. The difference can be explained by the insertion loss of the delay line (~1dB) and a bad splice in the lower arm. The loss of the upper arm was thereafter increased to the value of the lower one. The second fiber (after the coupling φ^*) consists of the same pass through the polarization interferometer as the first fiber. Note that for the two 'quasi PM' fibers to be aligned, φ^* has to be set to 90 deg (i.e. the coupling φ of above is 90 deg - φ^*). The coupling ratio can be easily determined by adjusting the input light to the || mode (see Fig.3) and measuring the decrease in power when blocking the delay line.

Fig. 4 shows interferometric DGD measurements of the emulator for a coupling φ of 0 deg and 90 deg (top), and of 45deg (bottom). For 90 deg (dashed curve), the fast axis of the first fiber is aligned with the slow one of the second fiber, and the corresponding peak therefore gives $|\Delta\tau_1-\Delta\tau_2|$. As discussed above, this difference should be zero as otherwise the ratio ξ slightly varies as a function of the delay line setting (i.e. for different values of the fiber DGDs $\Delta\tau_1$ and $\Delta\tau_2$). Due to the alignment of all PM fibers in our emulator (with the exception of φ^*), $|\Delta\tau_1-\Delta\tau_2|$ is in fact given by the DGD of the total length L of PM fiber passed from the emulator input to its output (passing both interferometer arms once). $|\Delta\tau_1-\Delta\tau_2|$ is therefore independent of the delay line setting (which was also verified experimentally), and amounts to 17.5 ps which corresponds well with the overall length L of ~10m. Note that for critical applications, this undesired effect could be completely removed by splicing a PM fiber with a DGD of 17.5 ps to the output, but now with the fast axis aligned with the slow emulator axis. Fig.4 further demonstrates that for a coupling of φ=0 deg, only a peak at $\Delta\tau_1+\Delta\tau_2$ is obtained, whereas for non-aligned fiber axes, peaks at $\Delta\tau_1$ and $\Delta\tau_2$ appear as well.

Having verified that the emulator DGD can be set by the delay line as desired, we measured the first and second order PMD for different coupling ratios, determined as described above. For the corresponding JME measurements, the emulator was put into a temperature controlled box to keep the output polarization stable with time. Fig.5 shows the corresponding results (circles) for a DGD setting of $\Delta\tau_1$=40.2 ps (and consequently $\Delta\tau_2$=22.7 ps). Once more, the agreement with the expected values (lines) is good. The small deviations from theory can be explained by both a slightly erroneous setting of the coupling ratio, and by the noise of the second order PMD measurements. This noise was measured by keeping a fixed wavelength in the JME, and amounts to ~0.06·DGD/(wavelength-stepsize). For a coupling of 1 e.g., this gives ~100 ps^2 for the employed stepsize of 0.05 nm.

Conclusions

We have presented a PMD emulator giving an adjustable DGD and ratio between first and second order PMD. The ratio is conserved for different values of the DGD, and valid for any wavelength channel.

Acknowledgements: We would like to thank B.Huttner (Luciol Instruments SA, Nyon) for his initial calculations, and acknowledge financial support from the Swiss Federal Office for Education and Science (within the framework of the European COST265 project) and from EXFO (Quebec).

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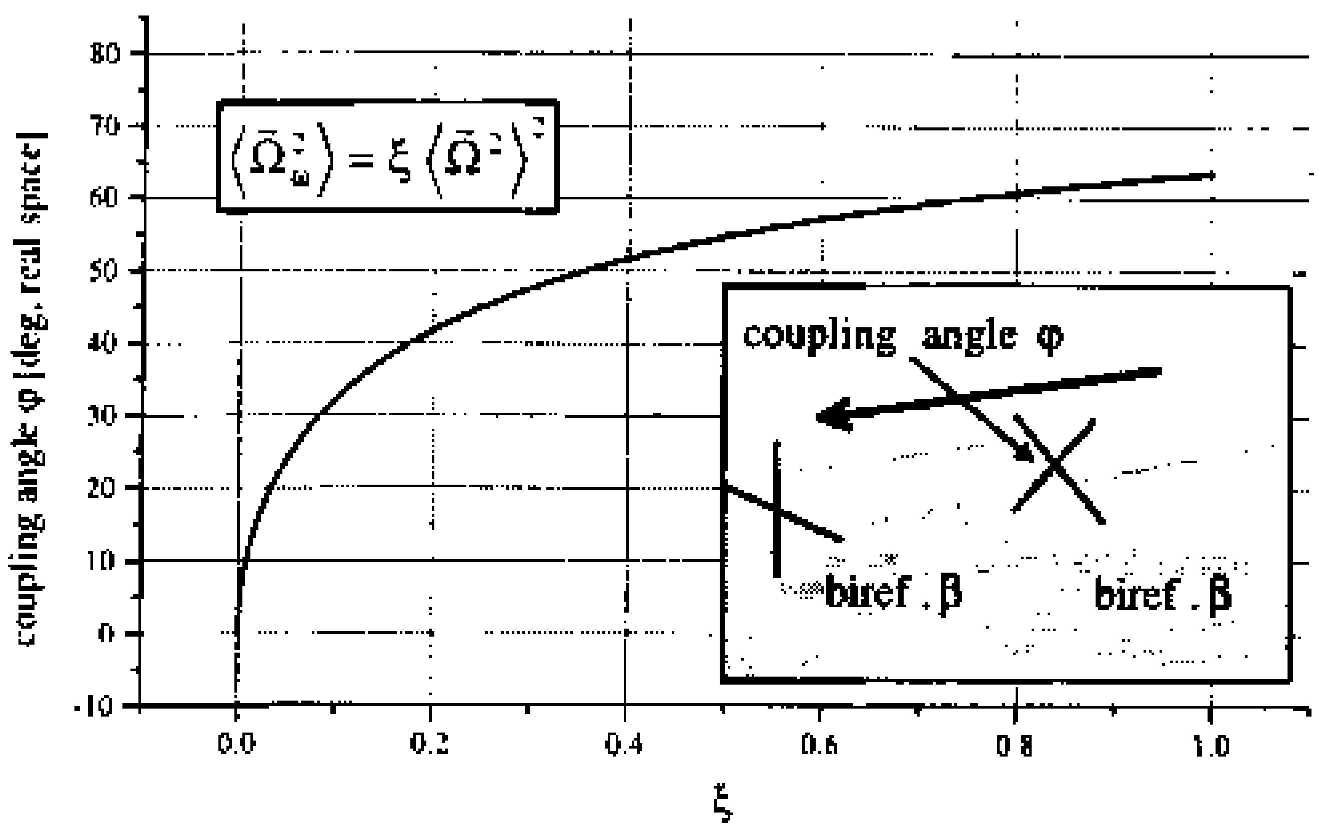

Fig.1: coupling angle φ necessary for a ratio ξ between 2^{nd} order and 1^{st} order PMD of a concatenation of two PM fibers with equal DGD

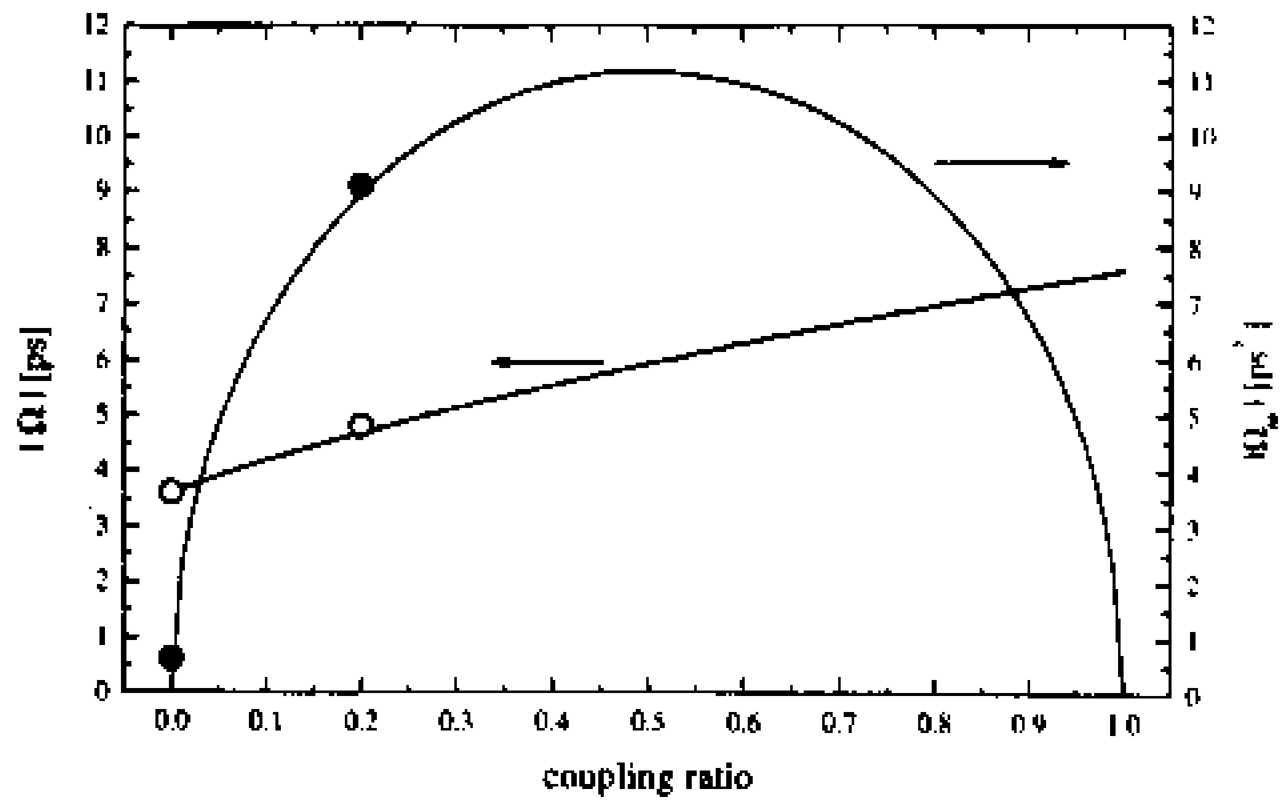

Fig.2: theoretical (lines) and measured (circles) 1^{st} and 2^{nd} order PMD for a concatenation of two PM fibers with DGDs of 2.0 and 5.65 ps and varying coupling

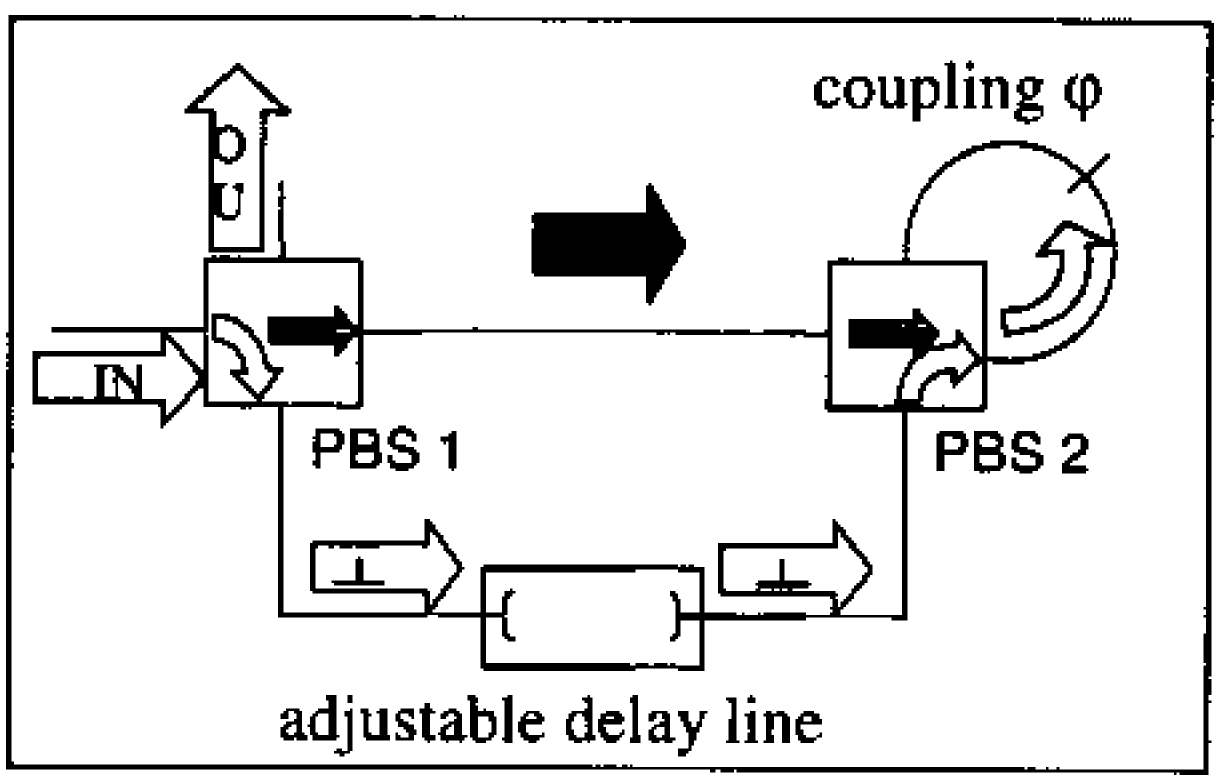

Fig.3: set-up of the PMD emulator. All fibers are polarization maintaining with their axes aligned

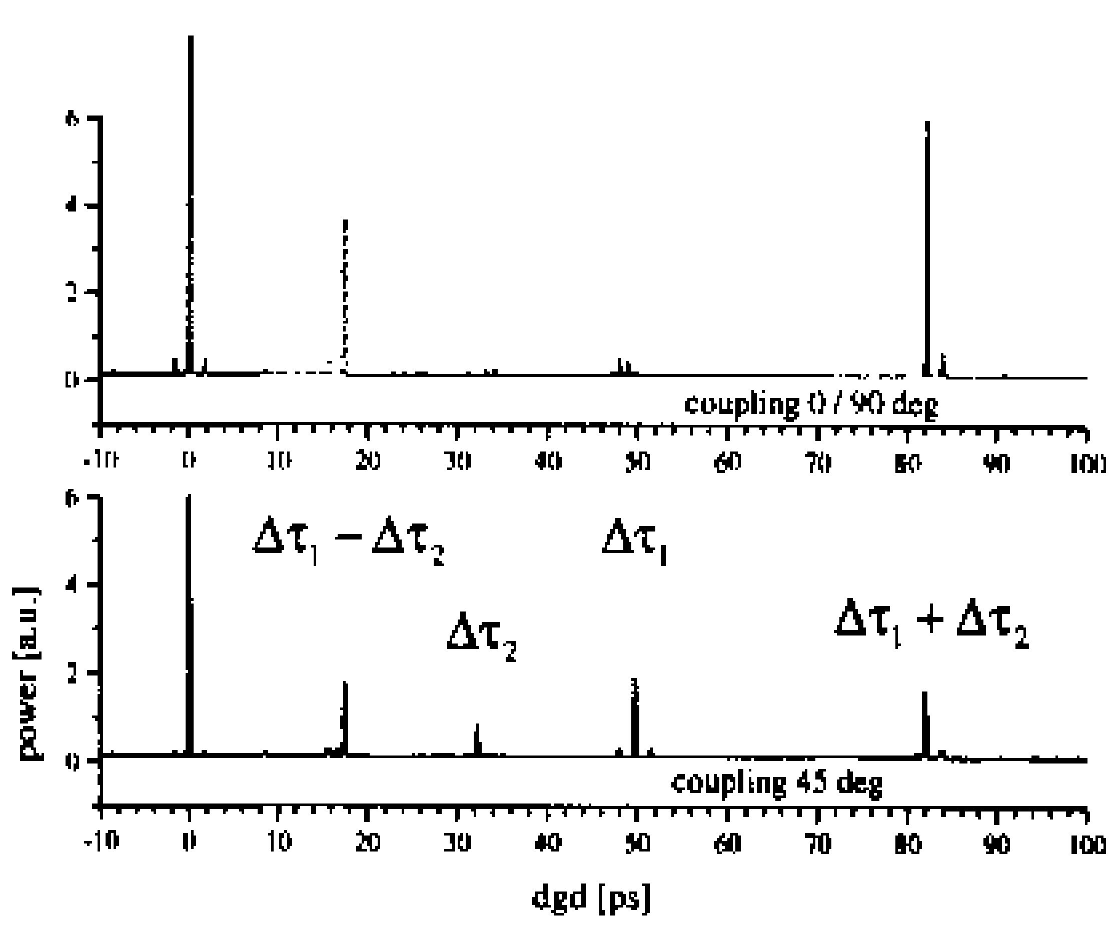

Fig.4: interferometric DGD measurement of the PMD emulator for a constant setting of the variable delay. dashed curve (top): φ=0deg, solid line (top): φ=90deg, solid line (bottom): φ=45deg

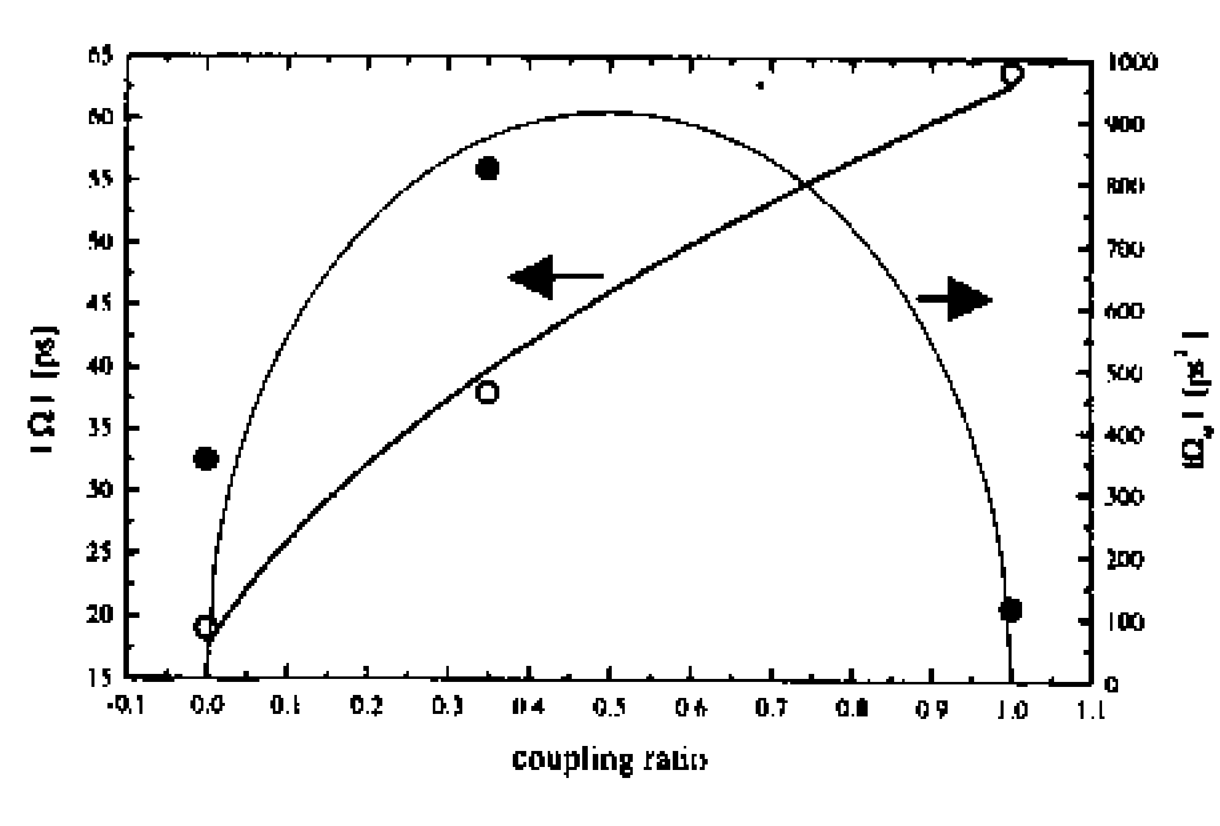

Fig.5: theoretical (lines) and measured (circles) 1^{st} and 2^{nd} order PMD of the PMD emulator for a DGD setting of $\Delta\tau_1$=40.2 ps ($\Delta\tau_2$=22.7 ps)