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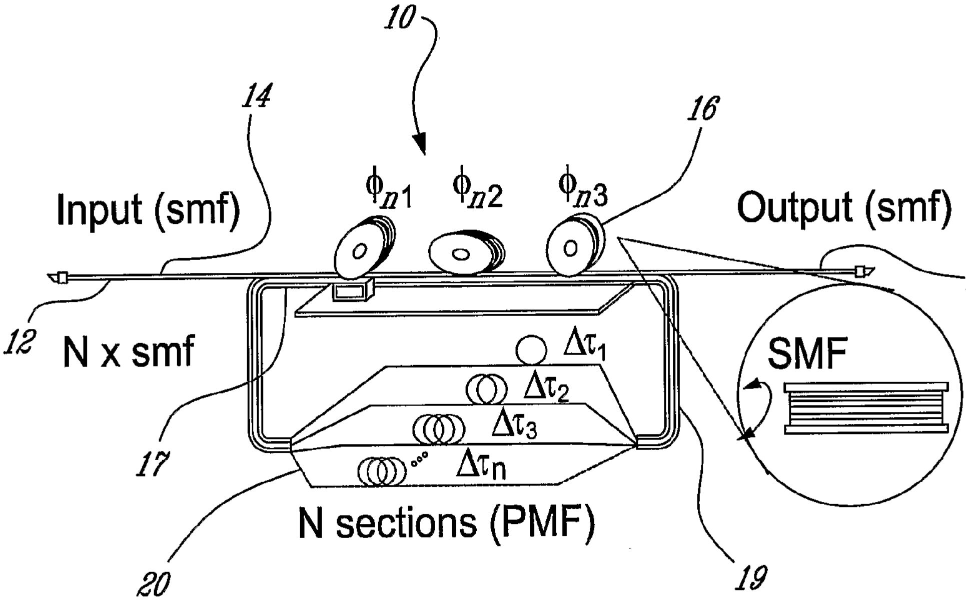
[Continued on next page]

(54) **Title:** POLARIZATION MODE DISPERSION EMULATOR



(57) **Abstract:** A polarization mode dispersion (PMD) emulator comprises a single mode fiber (SMF) signal input section, a SMF signal output section, first intermediate SMF sections between the input and the output sections, and second intermediate SMF sections between the input and the output sections. The first intermediate SMF sections are spooled about respective movable spooling members. Also, each of the second intermediate SMF sections is spliced with a respective polarization maintaining fiber (PMF) section, each of the PMF sections having a length defined by a fiber length distribution. The SMF signal input section, the first and second intermediate SMF sections, the PMF sections and the SMF signal output section define a series circuit with the first and second intermediate SMF sections alternating relative to one another.

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TITLE OF THE INVENTION

POLARIZATION MODE DISPERSION EMULATOR

FIELD OF THE INVENTION

[0001] The present invention generally relates to polarization mode dispersion emulators. More specifically, the present invention is concerned with polarization mode dispersion emulators using a single modified Lefèvre controller.

BACKGROUND OF THE INVENTION

[0002] Polarization mode dispersion (PMD) poses a serious impediment to the deployment of long haul optical fiber links transmitting in excess of 10 Gb/s per channel [H. Kogelnik, R. M. Jopson, and L. E. Nelson "Polarization-Mode Dispersion" in Optical Fiber Telecommunications IV B, I. Kaminow and T. Li, Eds. (Academic Press, San Diego, 2002), pp. 725-861]. A significant amount of research has been conducted into developing techniques to mitigate or compensate this impairment; however, so far, only partial success has been reported. An approach to study the effect of PMD in systems is to synthesize the impairment artificially using a PMD emulator. This tool can be used to test mitigation strategies and analyze system outages. It has the advantage of introducing a level of stability and control to the PMD generation process. To reliably and controllably generate PMD with the statistical distribution of a transmission link is cost effective but has the benefit of isolating the effect of PMD which is useful for many applications.

[0003] More specifically, PMD in a fiber arises from geometric or stress anisotrophy in the fiber core. The breakdown of circular symmetry induces modal birefringence in the fiber and thus two distinct polarization modes propagate at different speeds. If the birefringence axes of the fiber are fixed, only a simple differential group delay (DGD) is developed between the modes. However, realistically a long fiber link is described by a large number of locally fixed birefringence domains with random, time-varying mode coupling between them. The mode coupling introduces frequency dependence into the system, which causes signal waveform distortion. While the earlier first generation PMD emulators focused mainly on accurately emulating first order statistics, investigating higher bit rate systems requires that the frequency depedence of PMD also be replicated correctly.

[0004] The most commonly encountered emulator attempts to reproduce the PMD of a long fiber by employing a system consisting of a finite number of fixed length, highly birefringent elements separated by polarization rotating or scrambling stages. Typically the emulator elements are birefringent crystals or sections of polarizarion maintainting fiber (PMF) and thus are effectively locally achromatic and linearly birefringent. Adopting the mathematical formalism of Foschini and Poole [G. Foschini and C. Poole, "Statistical theory of polarization dispersion in single mode fibers," *J. Lightwave Technol.*, vol. 9, no. 11, pp. 1439–1456, 1991], each section is described by a frequency independent PMD vector Ω_i that lies on the equator of the Poincaré sphere in the Stokes space, and has a magnitude equal to the locally induced DGD.

[0005] For a system of N birefringent elements, the net PMD is obtained by taking the vector sum of each of the section contributions rotated into the same reference frame. Selecting the reference frame of the last section the net output PMD vector is given by:

$$\vec{\Omega}_{\mathrm{Tot}}(\omega,\vec{\theta}) = \vec{\Omega}_{\mathrm{N}}(\theta_{\mathrm{N}}) + \sum_{k=1}^{\mathrm{N}-1}\left(\prod_{i=0}^{\mathrm{N}-i-1}\mathbf{R}_{\mathrm{N}-1}\right)\vec{\Omega}_{k}(\vec{\theta}_{k}).$$

Where θ_N is the physical orientation of the waveplate, $\mathbf{R}_{N-1}$ is the rotation matrix and ω denotes the angular frequency.

[0006] Due to mode coupling occurring in both the emulator and the deployed fiber systems, the net output PMD vector is in general a function of frequency. A Taylor series expansion of $\Omega(\omega)$ about a given frequency ω_0 resolves the PMD into the commonly seen first and higher order component approximation,

$$\vec{\Omega}(\omega)=\vec{\Omega}(\omega_0)+\vec{\Omega}_{\omega}(\omega_0)[\omega-\omega_0]+\vec{\Omega}_{\omega\omega}(\omega_0)[\omega-\omega_0]^2+\ldots$$

where the higher order components explicitly describe the frequency dependence of the impairment.

[0007] When characterizing the performance of a PMD emulator, at a minimum the probability density function (PDF) of the magnitudes of $\Omega(\omega)$ and $\Omega_{\omega}(\omega)$ closely match those of a long fiber span. Also the frequency autocorrelation function for the PMD vector is given by:

$$\Gamma(\Delta\omega)=\frac{\langle \mathbf{\Omega}_{\mathrm{Tot}}(\omega_0)\cdot\mathbf{\Omega}_{\mathrm{Tot}}(\omega_0+\Delta\omega)\rangle}{\langle \mathbf{\Omega}_{\mathrm{Tot}}(\omega_0)\cdot\mathbf{\Omega}_{\mathrm{Tot}}(\omega_0)\rangle}$$

where the symbol <.> denotes ensemble averaging with respect to mode coupling configuration. The autocorrelation function decays rapidly towards zero outside the bandwidth of the principal states of polarization.

[0008] Clearly a PMD emulator employing a finite number of elements with fixed DGDs has the disadvantage in that the first order PMD statistics will be truncated. Similarly, the higher order PDFs will also be impacted. Nevertheless, if it can be made practical to include a large number of sections, i.e. the design is scalable, the disadvantage can be mitigated.

[0009] Therefore, emulator designs demonstrated in the literature, are typically based on concatenating a number of highly birefringent elements. By dynamically varying the polarization coupling between elements, for example with polarization controllers (PC), rotatable connectors or by thermally tuning the birefringence of the elements, different PMD states are generated. Independent mode coupling is implemented using a number of sections with separate polarization rotating devices. Since higher orders of PMD require an increasing number of emulator sections for their statistics to be accurately reproduced, the design has poor scalability. In practice, the number of sections required is typically limited to 30. Hence 30 polarization controllers are required. On the positive side, it is often sufficient to drive the polarization coupling randomly to reproduce the statistics of the various PMD orders affecting a long fiber link and using all-fiber components, such as the Lefèvre PC, results in a device with very low insertion loss.

[0010] Another demonstrated method for emulating the statistical behavior of PMD uses variable DGD elements. Any desired first order statistic can be obtained by deterministically controlling the DGD of the elements. This technique can emulate the first-order PMD with exact Maxwellian distribution by using only one DGD element but more are necessary for the generation of higher order PMD. The principal advantage is that a wide range of mean DGD can be obtained but the method requires more complex control. Variable DGD elements are more expensive than polarization controllers and have larger insertion losses and do not offer any advantage in the number of sections needed for low background autocorrelation.

[0011] Ideally a PMD emulator should emulate the proper statistical behavior of a transmission link for all orders of PMD and have a frequency autocorrelation function that tends to zero outside a limited bandwidth with the least number of elements possible. It should preferably be simply controlled, have a low insertion loss, low polarization-dependent loss and have flexible design parameters for low-cost manufacturing.

OBJECTS OF THE INVENTION

[0012] An object of the present invention is therefore to provide a polarization mode dispersion emulator which replaces the multiple coupling stages of a conventional emulator with a single modified Lefèvre polarization controller (PC).

[0013] Another object of the present invention is to provide a polarization mode dispersion emulator which is robust, compact, low-cost, having low polarization-dependent loss, low insertion loss and being flexible in design parameters.

[0014] Furthermore, through proper selection of design parameters, an object of the present invention is to provide a polarization mode dispersion emulator that can reproduce PMD statistics far into the PDF tail, where system outages are likely to occur.

[0015] Finally, another object of the present invention is to provide a polarization mode dispersion emulator which is scalable.

SUMMARY OF THE INVENTION

[0016] More specifically, in accordance with the present invention, there is provided a polarization mode dispersion (PMD) emulator comprising a single mode fiber (SMF) signal input section, a SMF signal output section, first intermediate SMF sections between the input and the output sections, and second intermediate SMF sections between the input and the output sections. The first intermediate SMF sections are spooled about respective movable spooling members. Also, each of the second intermediate SMF sections is spliced with a respective polarization maintaining fiber (PMF) section, each of the PMF sections having a length defined by a fiber length distribution. The SMF signal input section, the first and second intermediate SMF sections, the PMF sections and the SMF signal output section define a series circuit with the first and second intermediate SMF sections alternating relative to one another.

[0017] The foregoing and other objects, advantages and features of the present invention will become more apparent upon reading of the following non-restrictive description of illustrative embodiments thereof, given by way of example only with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] In the appended drawings:

[0019] Figure 1 is a schematic diagram of a PMD emulator using a single PC according to an embodiment of the present invention;

[0020] Figures 2a, 2b and 2c illustrate examples of PC rotation distributions according to the Poincaré sphere;

[0021] Figure 3 illustrates the probability density function vs DGD from simulating the embodiment according to the present invention as illustrated in Figure 1.

[0022] Figure 4 is a graph showing the Normalized Deviation Factor vs the number of sections for the first order statistics;

[0023] Figure 5 is a graph showing the Normalized Deviation Factor vs the number of sections for the second order statistics;

[0024] Figure 6 is a graph illustrating the simulated auto-correlation function of an emulator using independent polarization controllers;

[0025] Figure 7 is a graph illustrating the simulated auto-correlation function of an emulator using a single modified controller;

[0026] Figure 8 is a graph illustrates the background auto-correlation vs the number of sections.

DETAILED DESCRIPTION

[0027] Figure 1 illustrates a PMD emulator 10 in accordance with an embodiment of the present invention. The PMD emulator 10 can be described via a vector $\Omega(\omega)$ in the Stokes space, where ω is the angular optical frequency [G. Foschini and C. Poole, "Statistical theory of polarization dispersion in single mode fibers," *J. Lightwave Technol.*, vol. 9, no. 11, pp. 1439–1456, 1991]. The PMD vector is derived from the frequency dependence of the Jones matrix [B. L. Heffner "Deterministic, analytically complete measurement of polarization-dependent transmission through optical devices", Photon. Tech. Lett., 4(5), 451–454 (1992)] expressed as:

$$T(\omega) = \prod_{n=0}^{N} R(-\alpha_n)\, B(\Delta\tau_n, \omega)\, PC(\Theta_n, \Phi_n)\, R(\alpha_n)$$

where **R** is the rotation matrix, α_n represents the axis of alignment for the n^{th} section, **PC** is the transfer matrix for the PC of the n^{th} section where $\theta_n = [\theta_{1n}, \theta_{2n}, \theta_{3n}]$ are the angles of each of the three paddles of the PC and $\Phi_n = [\Phi_{1n}, \Phi_{2n}, \Phi_{3n}]$ are the differential phase delays of each paddle. $\mathbf{B}(\Delta\tau_n, \omega)$ is the frequency dependent transfer matrix for the element of the n^{th} section with fixed DGD $\Delta\tau_n$. The DGD (Differential Group Delay) for the PMD emulator can be found by calculating the eigenvalues of the matrix $\delta_\omega T(\omega)T^{-1}(\omega)$. A more detailed description of the PMD emulator 10 with its various components will be given hereinbelow.

[0028] Furthermore, the PMD emulator 10 is part of a new class of multi-section PMD emulators employing degenerate polarization scrambling (DPS) for which the matrices describing the polarization rotations are correlated. Typically this would be due to PC component reuse. For example, in the case of a single PC emulator, with standard single mode fiber (SSMF) spliced to sections of polarization maintaining fiber (PMF) and wound up onto three paddles of a Lefèvre polarization controller, the rotation matrix associated with the j^{th} polarization scrambling stage is given by the product of the Müller matrices describing the retardations due to the three PC paddles:

$$\mathbf{C}_j = \mathbf{S}_3(\theta_3, \phi_3^{(j)})\mathbf{S}_2(\theta_2, \phi_2^{(j)})\mathbf{S}_1(\theta_1, \phi_1^{(j)})$$

where $\theta_i \in [-\pi/2, \pi/2]$ is the physical orientation of the i^{th} waveplate relative to a fixed observer reference frame and $\Phi_i^{(j)} \in [0, 2\pi]$ is the phase delay. The polarization scrambling is degenerate because each stage's waveplates are implemented using the same PC paddles, and thus have the same θ_i.

[0029] However, the fixed waveplate retardations can be arbitrarily chosen by winding the SMF for each PC stage a different number of turns around the paddles, thus allowing degeneracy to be at least partially broken.

[0030] Returning to Figure 1, the PMD emulator 10 comprises a single mode fiber (SMF) 12 with an input section 14 and an output section 18. A first intermediate SMF section 17 is defined between the input section 14 and the output section 18 of the SMF 12. In this interval, movable spooling members such as movable paddles 16 of a simple customized Lefèvre polarization controller (PC) are so positioned and configured as to allow the first intermediate SMF section 17 to be wound thereon. In this non-limitative example, there are three such paddles 16. Furthermore a second intermediate SMF section 19 is defined between the input section 14 and the output section 18 of the SMF 12 and is spliced to respective sections 20 of polarization maintaining fiber (PMF), each PMF section 20 having a predetermined length. As it can be seen in Figure 1, the first and second intermediate SMF sections 17 and 19 respectively alternate relative to each other. A plurality of such alternating first and second intermediate SMF sections 17 and 19 can be defined and are referred to as the number of sections. Such number of turns around the paddles 16 is chosen arbitrarily according tho the needs of the skilled artisan in the art. With such a setting of the PMD emulator 10, several parameters can be determined, such as the number of sections N, the differential group delay (DGD) $\Delta\tau_n$, the length of each PMF section 20, the splicing angle (α_n) between SMF and PMF sections, and the phase delays (Φ_n) of the paddles 16 in order to produce a PMD emulator.

[0031] The SMF 12 is a standard single mode fiber, well known in the art. Consequently, SMFs will not be further discussed in the present specification.

[0032] The paddles 16 are generally motorized and rotated continuously using generic electrical motors (not shown). Each motor has a constant speed but a slightly different constant voltage is applied to each one of the motors. Thus, by randomly moving/rotating the paddles laterally with respect to the direction of input signals, the mode coupling between each one of the paddles of the PC is randomly varied, which allows for generating different PMD states. It has been shown that three such paddles 16 can generate any desired polarization states, even though it is not necessary to have three paddles. Simulations with two paddles showed poor performance of the emulator. Of course, four or more such paddles 16 can be used. However, an increased number of paddles greatly increases the complexity of the PMD emulator 10. The tradeoff between gain in performance and complexity depends on the needs of the intended application of the PMD emulator 10. Furthermore, the design of the paddles 16 allows for multiple independent fibers to be spooled as illustrated in Figure 1.

[0033] In an embodiment of the present invention, for example, the diameter of the paddles 16 are such that a relative phase delay of π/6 is induced per turn at a wavelength of 1550 nm when using standard single mode fiber.

[0034] Also, the three paddles 16 induce phase delays (Φ_{1n}, Φ_{2n}, Φ_{3n}). Phase delays can be changed on the paddles 16 for each of the sections 17 in order to create randomness in phase delays. Efficient randomization over the entire Poincaré sphere is typically achieved with ¼ λ, ½ λ, ¼ λ (QHQ) differential phase delays for the three paddles 16 of a Lefèvre polarization controller. A waveplate with a phase delay of π provides a longitudinal transformation to the input polarization on the Poincaré sphere. In other words, a QHQ configuration uniformly spans all possible polarization states, given any arbitrary input. This is translated into a phase delay of π for one of the three paddles. Figures 2a, 2b and 2c illustrate the spanning of the Poincaré sphere for different PC configurations where the three coupling angles between paddles are randomly varied. By using different configurations the polarization rotation may no longer be uniformly distributed as shown for the non-uniform longitudinal spanning configurations. Correlation between stages is therefore reduced by ensuring that only PCs applying a rotation that uniformly spans the longitudinal angles on the Poincaré sphere are used.

[0035] Returning to Figure 1, highly birefringent PMF 20 is provided for splicing to each respective section of the SMF 12. Each section of PMF 20 has a different length which is determined by a PMF length distribution function. Such length distribution function includes uniform distribution (equal length for each section), exponential distribution, Gaussian distribution and Maxwellian distribution. The number of sections is arbitrary and will depend on the needs of the intended application. The larger is the number of sections, the higher is the order of the PMD statistical distribution that can be established. An example showing the parameters used in a PMD emulator 10 is given in Table 1.

Table 1 : Parameters of the PMD emulator

Number of sections	25
PMF Length distribution	Gaussian
Section #	Phase delays
1, 6, 11, 16, 21	π/2, π, π/2
2, 7, 12, 17, 22	π/3, π, π/3
3, 8, 13, 18, 23	π/6, π, π/6
4, 9, 14, 19, 24	5π/6, π, 5π/6
5, 10, 15, 20, 25	2π/3, π, 2π/3

[0036] In this example, it was shown that using a sufficient number of different sets of phase delays has a similar effect as using independent scrambling stages. Furthermore, the PMF length induces a differential group delay (DGD). By randomizing each section's DGD, the polarization of the light entering successive stages of the emulator is effectively scrambled. However, the birefringence axes of the PMF 20 must be similarly randomized. Using the rule that selects the PMF length using a Gaussian probability distribution with means such that an equal section emulator would give an average system DGD of 30 ps and standard deviations of 20%, acceptable results were consistently obtained and even the statistics on a linear scale as opposed to logarithmic scale were improved.

[0037] A splicing angle α_n refers to the angle that the fast axis of the PMF 20 forms with the PC. Mathematically, this splicing is modeled by sandwiching the PC Jones matrices between rotation matrices. It should be noted that in practice the splicing angles connecting the PMF sections to the PC stages are both random and different. It was found numerically that if all the splicing angles were aligned, it inappropriately skews the PDF of PMD. In a conventional emulator design identical splicing angles have little effect on the PDF. By uniformly randomizing the orientations of the splicing angles, some of the degeneracy is broken and simulations show a dramatic improvement in the statistic. Those of ordinary skill in the art will understand that the influence of the angle of the paddles 16 has a small effect on the splicing angle.

[0038] The design parameters for an embodiment of the present invention comprise the number of sections N, the set of differential group delays (DGD) $\Delta\tau = [\Delta\tau_1, \Delta\tau_2, \ldots, \Delta\tau_n, \ldots, \Delta\tau_N]$, the length of the PMF sections, the phase delays (Φ_{1n}, Φ_{2n}, Φ_{3n}), for n=1 to n=N, and the splicing angles $\alpha = [\alpha_1, \alpha_2, \ldots, \alpha_n, \ldots, \alpha_N]$ between stages of the emulator. Unlike conventional emulators, the PMD emulator 10 design limits the number of variables for accessing different PMD states to the three coupling angles between the PC paddles (since three paddles 16 are used in an embodiment of the present invention). The tradeoff for this reduced complexity is a greater likelihood of correlation in the PMD statistics (or degeneracy), leading to skewed probability density functions for all orders of PMD. Properly setting the above mentioned parameters minimizes the correlation in polarization rotations between successive sections.

[0039] Another embodiment of the present invention is concerned with the deterministic case when the rotating paddles are given specific values. By doing so, a table of values can be generated and then used to map the characteristics of the PMD.

EXAMPLES

[0040] The invention will be further exemplified by the following non-restrictive illustrative examples.

[0041] A first scenario for experimental setup for Monte Carlo simulations consists of:

- having equal length PMF sections 20;
- having all the splicing angles aligned with each other and passing through the PC wound into a standard QHQ (¼ λ, ½ λ, ¼ λ) waveplate configuration;
- having 25 SMF sections with 5 sets of phase delays as illustrated in Table 1.

[0042] A second example uses the same information as given in the first scenario with the exception that the PMF length is distributed with a Gaussian distribution this time. Furthermore, further simulations have been performed with the number of sections N set to 15, 30 and 50.

RESULTS

[0043] The graph of Figure 3 shows the effect of the alignment of the PMF sections to the PC on the probability density function (PDF) of the first order PMD. Randomizing the alignment improves the PDF, something that is not observed in standard emulators. Results in the graph of Figure 3 show also that PC phase delays make the first and second order statistics indistinguishable from the theoretically predicted distributions on a linear scale.

[0044] Experimental data, obtained using an Adaptif Photonics polarization analyzer, show a good match to the simulations except that the tails of the first and second order statistics are not well emulated above approximately 2.5 times the mean DGD. Simulation for a 30 section standard emulator shows that it accurately emulates PMD just over three times the mean DGD. The single PC PMD emulator design scales efficiently. Simulation and experimental results shown using 50 sections considerably diminishes the effect of the degeneracy in the PC. With increased number of sections, the single polarization controller PMD emulator promises to reproduce the tail of the PMD curve beyond any values practically achievable until now.

[0045] A commonly used parameter to analyze the statistics of a PMD emulator is the deviation factor defined as $\sum_i |PDF_{emul}(x_i) - PDF_{theory}(x_i)|^2$, where $PDF_{emul}(x_i)$ and $PDF_{theory}(x_i)$ are probability density functions for the emulator and the theoretical prediction for a long fiber link for the PMD order considered. But this definition has the disadvantage of overestimating the importance of theoretical PDF matching in the peak of the distribution at the expense of the tail where system outages are most likely to occur. We use here a normalized deviation factor which puts more emphasis in the tail of the distribution. The graph of Figure 4 compares the normalized deviation factor of first order PMD as a function of the number of sections for the single PC emulator versus a standard independent scrambling stages emulator. It indicates that independent polarization scrambling leads to better results for the same number of sections. The main advantage of the single PC design is that it is scalable so that a 50 section single PC emulator is much easier to fabricate than a 15 sections independently controlled emulator and provides much better theoretical match. The graph of Figure 5 compares the second order statistcs of the two types of emulator from which the same conclusion can be drawn.

[0046] The frequency auto-correlation function of the PMD emulator when averaged over an ensemble of fiber realizations, should tend toward zero outside a limited frequency range to provide accurate broadband PMD emulation for WDM channels. Uncorrelated broadband PMD emulation is required in the study of broadband mitigation strategies. The auto-correlation functions tend to zero with just a few sections in a standard independently scrambled PMD emulator design as shown in the graph of Figure 6. In the single PC emulator design, a similar behavior is observed as shown in the graph of Figure 7. Plotting the simulated background auto-correlation vs the number of sections in the graph of Figure 8 indicates that both design provide similar performance for broadband PMD emulation even though a single PC design is a much simpler device. In comparison, a three element variable DGD PMD emulator which provides very good first and second order statistics, has around 50% background auto-correlation which makes them unsuitable in the testing of broadband PMD mitigation strategies.

[0047] Although the present invention has been described in the foregoing specification by means of a non-restrictive illustrative embodiment, this illustrative embodiment can be modified at will within the scope of the appended claims without departing from the spirit and nature of the subject invention.

WHAT IS CLAIMED IS:

1. A polarization mode dispersion (PMD) emulator comprising:

a single mode fiber (SMF) signal input section;

a SMF signal output section;

first intermediate SMF sections between the input and the output sections, the first intermediate SMF sections spooled about respective movable spooling members; and

second intermediate SMF sections between the input and the output sections, each of the second intermediate SMF sections spliced with a respective polarization maintaining fiber (PMF) section, each of the PMF sections having a length defined by a fiber length distribution;

wherein the SMF signal input section, the first and second intermediate SMF sections, the PMF sections and the SMF signal output section define a series circuit with the first and second intermediate SMF sections alternating relative to one another.

2. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the spooling members are laterally movable relative to a longitudinal direction of the first intermediate SMF sections spooled thereon.

3. A polarization mode dispersion (PMD) emulator according to claim 2, wherein the spooling members are laterally movable from an angle of about $-\pi/2$ to $+\pi/2$.

4. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the number of movable spooling members is three.

5. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the movable spooling members are generally circular and of a diameter such that a single winding of the SMF fiber induces a phase delay of $\pi/6$.

6. A polarization mode dispersion (PMD) emulator according to claim 1, further comprising an actuator associated with each of the movable spooling members.

7. A polarization mode dispersion (PMD) emulator according to claim 6, wherein the actuators move their respective movable spooling members at random.

8. A polarization mode dispersion (PMD) emulator according to claim 6, wherein the actuators move their respective movable spooling members to specific angular positions so as to emulate a desired polarization state, the specific angular positions being predetermined by mapping a plurality of angular positions with their resulting polarization states.

9. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the fiber length distribution is selected from the group consisting of: Gaussian, uniform, Maxwell and exponential distributions.

10. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the first intermediate SMF sections are spooled about their respective movable spooling members a predetermined number of times so as to reduce degenerancy.

11. A polarization mode dispersion (PMD) emulator according to claim 1, wherein each of the second intermediate SMF sections is spliced with its respective polarization maintaining fiber (PMF) section at various predetermined splicing angles.

12. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the number of alternating first and second intermediate SMF sections is at least 15.

13. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the number of alternating first and second intermediate SMF sections is at least 25.

14. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the number of alternating first and second intermediate SMF sections is at least 30.

15. A polarization mode dispersion (PMD) emulator according to claim 1, wherein the number of alternating first and second intermediate SMF sections is at least 50.

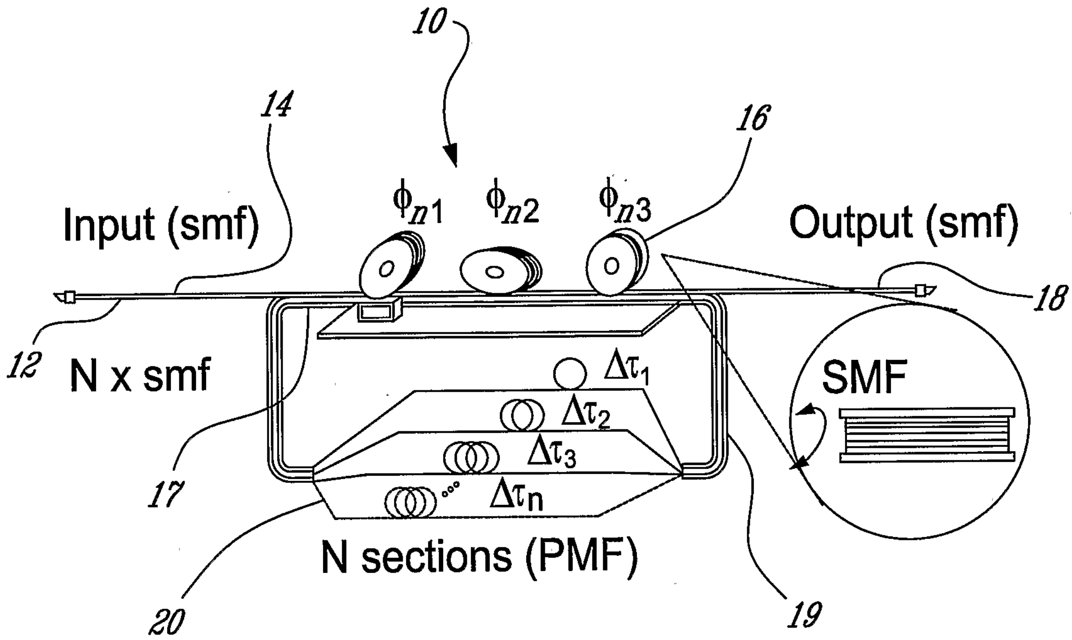
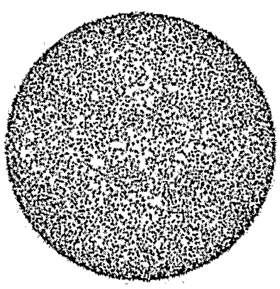
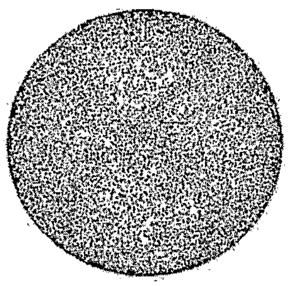

10
14
16
Input (smf)
$\phi_{n}1$
$\phi_{n}2$
$\phi_{n}3$
Output (smf)
18
12
N x smf
SMF
$\Delta\tau_1$
$\Delta\tau_2$
$\Delta\tau_3$
$\Delta\tau_n$
17
N sections (PMF)
20
19

Fig. 1



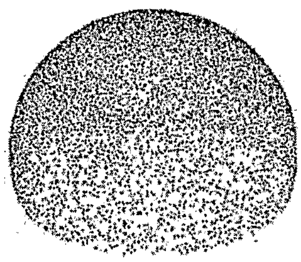
$\frac{\pi}{2}-\pi-\frac{\pi}{2}$

Fig. 2a



$\frac{\pi}{2}-\frac{\pi}{4}-\frac{\pi}{2}$

Fig. 2b



$\frac{\pi}{6}-\pi-\frac{\pi}{6}$

Fig. 2c

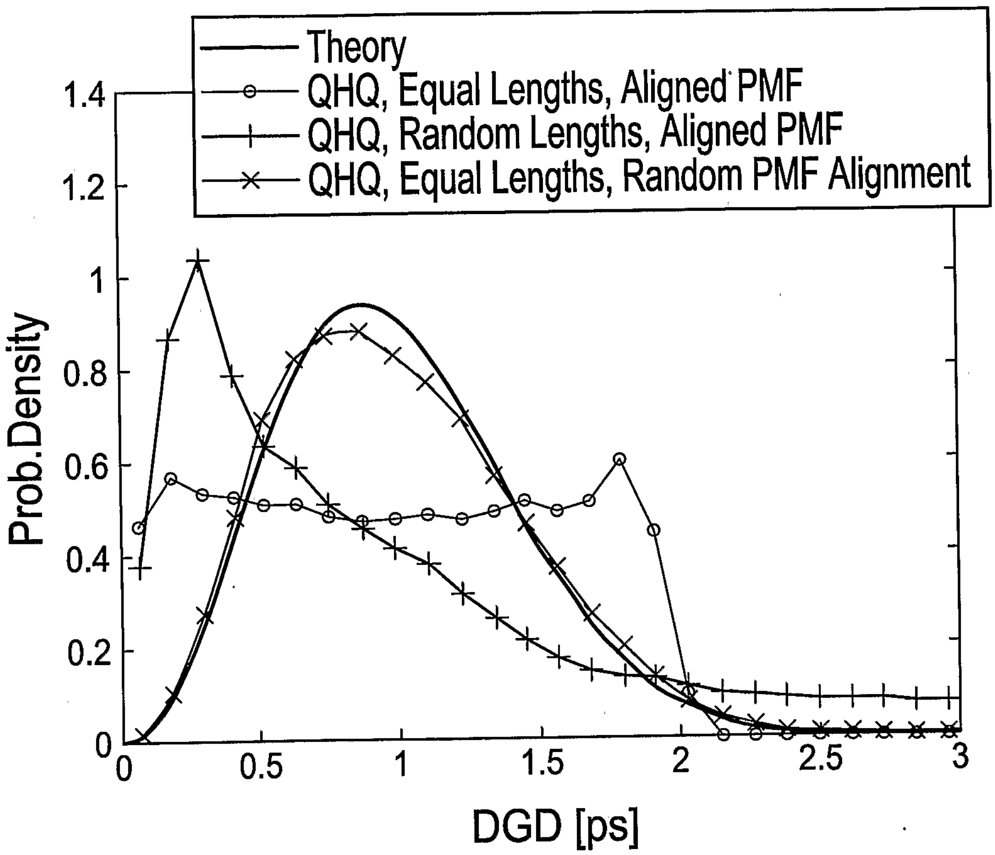

Theory
QHQ, Equal Lengths, Aligned PMF
QHQ, Random Lengths, Aligned PMF
QHQ, Equal Lengths, Random PMF Alignment
Prob.Density
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
DGD [ps]

Fig. 3

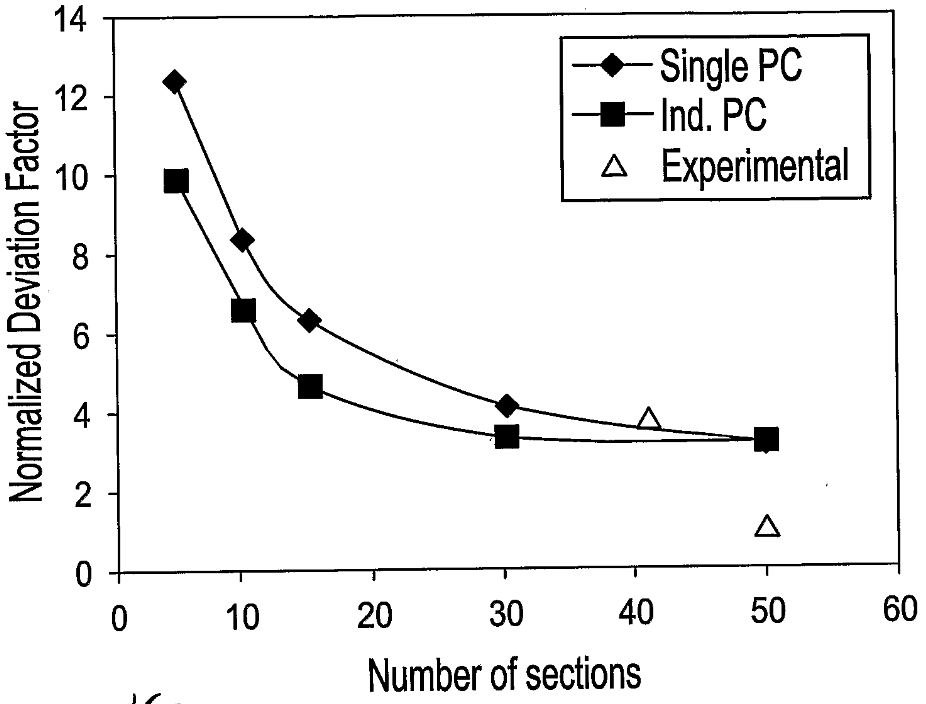

14
12
10
8
6
4
2
0
Normalized Deviation Factor
0
10
20
30
40
50
60
Number of sections
Single PC
Ind. PC
Experimental

Fig. 4

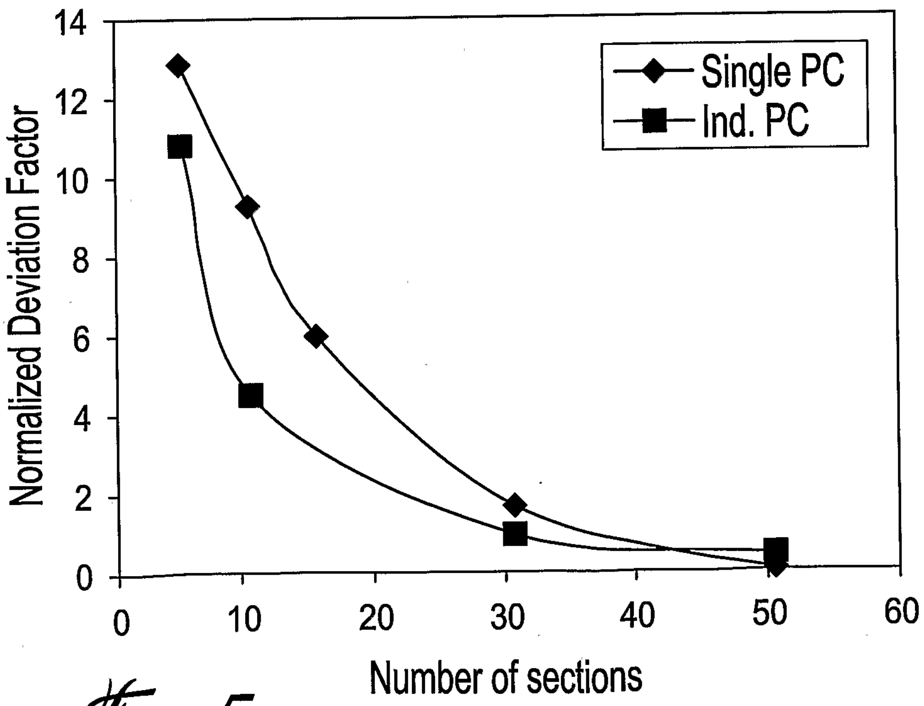

14
12
10
8
6
4
2
0
Normalized Deviation Factor
0
10
20
30
40
50
60
Number of sections
Single PC
Ind. PC

Fig. 5

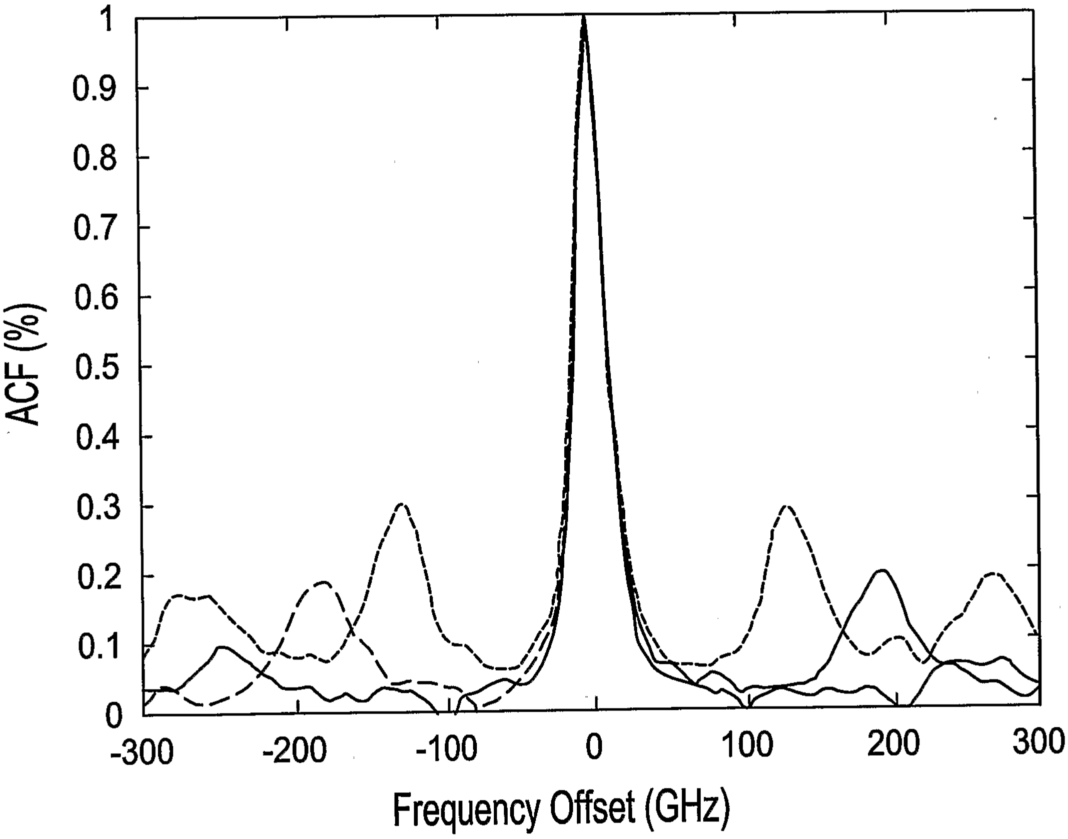

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ACF (%)
-300
-200
-100
0
100
200
300
Frequency Offset (GHz)

Fig. 6

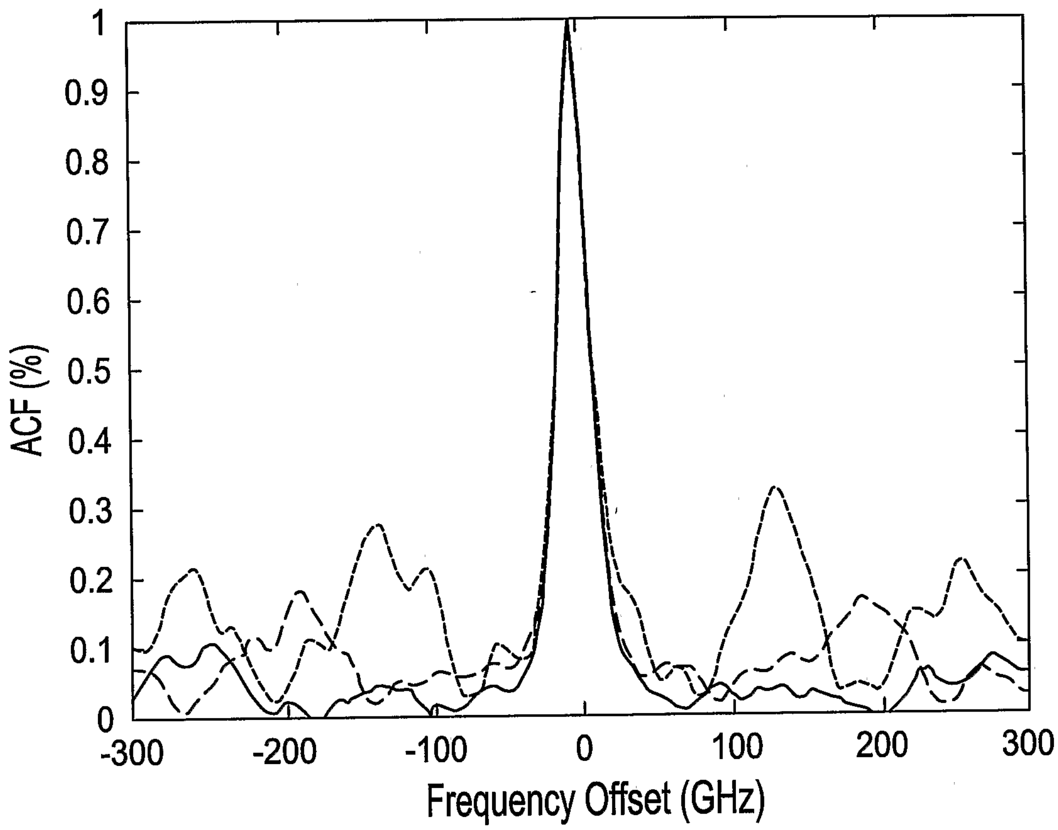
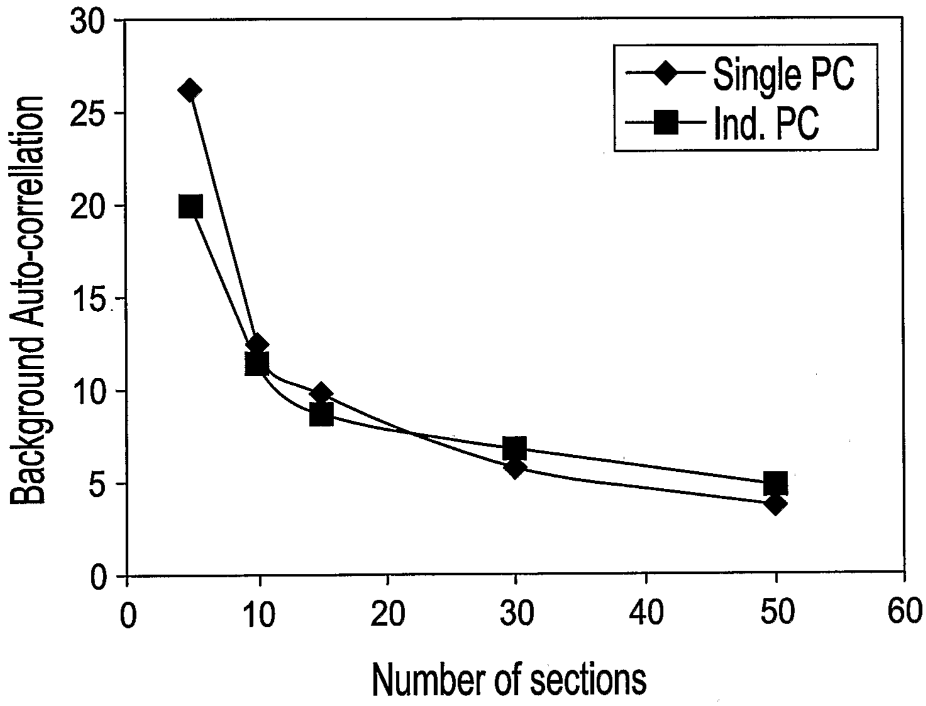

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ACF (%)
-300
-200
-100
0
100
200
300
Frequency Offset (GHz)

Fig. 7



30
25
20
15
10
5
0
Background Auto-correlation
Single PC
Ind. PC
0
10
20
30
40
50
60
Number of sections

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2006/000366

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***G02B 6/10*** (2006.01) , ***H04B 10/18*** (2006.01) , ***G02B 6/34*** (2006.01) , ***G02B 6/024*** (2006.01)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC :**G02B 6/10** (2006.01) , **H04B 10/18** (2006.01), **G02B 6/34** (2006.01), **G02B 6/024** (2006.01), **G02B 27/028** (2006.01), **G02F 1/00** (2006.01), **H04B 10/18** (2006.01)

US Classification : 359/497, 359/499, 398/152, 398/158, 398/159, 398/161, 385/11

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
None

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Delphion Espacenet US West Database Japanese Patent Database IEEE Online database SCOPUS

search terms used : polari?ation, dispersion, emulat*, simulat*, fiber, fibre, lefevre, control*, frequency

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	"PDL effects in PMD emulators made out with HiBi fibers: building PMD/PDL emulators" Photonic Technology Letters, IEEE DOS SANTOS ET AL. 28 February 2004 (28-02-2004) Vol. 16, Issue No. 2 pgs. 452 - 454 ISSN: 1041-1135 entire document	1 to 15
A	"Design and optimization of polarization mode dispersion emulators for low background autocorrelation" Technical Digest - OFC Conference, 2005 PALMER ET AL. 06 March 2005 (06-03-2005) Vol. 4 pgs. OThT3 (3 pgs. total) ISBN : 1-55752-783-0 entire document	1 to 15

[ ] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents :
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 June 2006 (15-06-2006)	20 June 2006 (20-06-2006)

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Authorized officer
Daniel Weslake (819) 997-2999

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date

NONE