(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
18 March 2004 (18.03.2004)

PCT

(10) International Publication Number
WO 2004/023680 A1

(51) International Patent Classification[7]: H04B 10/06, 1/10, H03D 1/06

(21) International Application Number: PCT/US2003/018867

(22) International Filing Date: 13 June 2003 (13.06.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/233,917 3 September 2002 (03.09.2002) US

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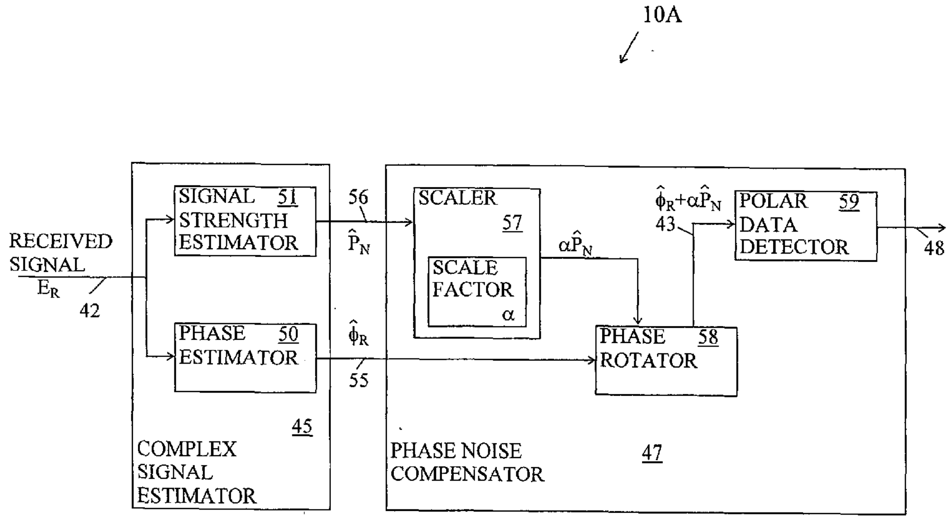
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** OPTICAL RECEIVER HAVING COMPENSATION FOR KERR EFFECT PHASE NOISE



(57) **Abstract:** A method and apparatus for reducing nonlinear phase noise that is induced in an optical transmission system by the interaction of optical amplifier noise and Kerr effect. The apparatus includes an intensity-scaled nonlinear phase noise compensator (47). The phase noise compensator reduces the nonlinear phase noise by rotating a phase estimate by a scaled signal strength estimate (56) for the optical signal or by comparing a complex estimate (55, 56) to curved regions having scaled nonlinear decision boundaries. The scale factor is derived from the number of spans in the transmission system. Another embodiment of the phase noise compensator uses the scaled signal strength for re-modulating an optical signal.

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OPTICAL RECEIVER HAVING COMPENSATION FOR KERR EFFECT PHASE NOISE

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to optical transmission systems and more particularly to apparatus and methods for reducing the effect of nonlinear phase noise caused by the interaction of optical amplifier noise and Kerr effect.

Description of the Prior Art

For a system with many fiber spans having an optical amplifier in each span to compensate for fiber loss, a simplified mathematical description assumes that each optical amplifier launches the same average signal power and each fiber span has the same length. The launched signal, represented by baseband equivalent electrical field entering the first span is to $E_1 = E_0 + n_1$, where E_0 is the baseband representation of the transmitted electrical signal as a complex number and $n_1 = x_1 + jy_1$ is the baseband representation of optical amplifier noise as zero-mean complex Gaussian noise with variance of $E\{|n_1|^2\} = 2\sigma^2$, where σ^2 is the noise variance per span per dimension and $E\{.\}$ denotes expectation. In the representation $n_1 = x_1 + jy_1$, the quadrature components x_1 and y_1 are zero-mean real Gaussian noise with variances $E\{|x_1|^2\} = E\{|y_1|^2\} = \sigma^2$. The simplest phase-modulated system uses binary phase shift keyed (BPSK) modulation where the binary "0" and "1" are modulated onto a carrier by a carrier phase shift of 0 or π, respectively. For a BPSK system, $E_0 = +A$ or $-A$ when "1" or "0" is transmitted, respectively, where A is a real number for the amplitude of the transmitted signal.

After the first in-line amplifier, the launched signal entering the second span is equal to $E_2 = E_0 + n_1 + n_2$, where n_2 is the amplifier noise from the optical amplifier of the second span. The statistical properties of n_2 are the same as those of n_1. At the end of amplifier chain after the Nth fiber span the signal becomes $E_N = E_0 + n_1 + \ldots + n_N$ entering the Nth fiber span with noise from all N amplifiers, where n_k, $k = 1...N$, is the noise from the kth fiber span, which has the same statistical properties as n_1. For a simplified mathematical description, one may assume that the signal arriving at the receiver is equal to E_N by ignoring the fiber loss of the last fiber span and the optical amplifier required to compensate for it.

Fig. 1 is an exemplary vector representation of a BPSK signal of "1" or "0" having constellation points with a phase of either 0 or π, respectively. Of course, any two phases that are separated by π may be used to represent "1" and "0". The vector representation is shown on a complex plane having an x-axis **12**, a y-axis **13**, and an origin **14** at the intersection of the x and y axes **12** and **13**. The signal "1" is transmitted as represented by a vector **15**. A vector **16** represents amplifier noise of a complex number of $n_1 + \ldots + n_N$ in the absence of other effects. A vector **17** represents a received signal E_N **15** with the effect of amplifier noise **16** without including an interaction of the amplifier noise and Kerr effect.

In this application the interaction of the amplifier noise and the Kerr effect is called Kerr effect phase noise. Gordon and Mollenauer in "Phase noise in photonic communications systems using linear amplifiers," *Optics Letters*, vol. 15, no. 23, pp. 1351-1353, Dec. 1, 1990 describe the effects of the interaction of optical amplifier noise with Kerr effect in an optical fiber communication system. With the Kerr effect, the refractive index of an optical fiber increases linearly with the optical intensity in the fiber. In each span of optical fiber, the Kerr effect phase noise is equal to $-\gamma L_{\text{eff}} P$, where γ is the nonlinear coefficient of the optical fiber, L_{eff} is the effective nonlinear length per span, and P is the optical intensity. The unit of electrical field is defined herein such that the optical intensity or power is equal to the absolute square of electric field. The nonlinear phase shift is usually represented by a negative phase shift in majority of the literature. The usage of positive phase shift does not change the physical meaning of the nonlinear phase shift. Herein, unless otherwise noted, the notation of negative phase shift is used.

A nonlinear phase noise is accumulated span after span due to the Kerr effect phase noise. The accumulated nonlinear phase noise is shown in an equation 1 below as nonlinear phase shift ϕ_{NL}, and denoted as an angle **18**:

$$\phi_{\text{NL}} = -\gamma L_{\text{eff}} \left\{ |E_0 + n_1|^2 + |E_0 + n_1 + n_2|^2 + \cdots + |E_0 + n_1 + \cdots + n_N|^2 \right\}. \qquad (1)$$

The nonlinear phase shift ϕ_{NL} **18**, which can also be represented by an electric field change vector **19**, results in a received signal **20**, which is the vector E_N **17** rotated by the nonlinear phase shift ϕ_{NL} **18**. Mathematically, the actual received electrical field **20** is $E_R = E_N \exp(j\phi_{NL})$. Because the actual received signal **20** is the rotated version of the signal plus noise vector **17**, the intensity of the received signal **20** does not change due to nonlinear phase shift, i.e., $P_N = |E_N|^2 = |E_R|^2$.

In a long transmission system with many fiber spans, both the noise vector **16** and the nonlinear phase shift ϕ_{NL} **18** are accumulated span after span. The incremental nonlinear phase noise angle of the kth span is $-\gamma L_{\text{eff}} \mid E_0 + n_1 + \cdots + n_k \mid^2$ and is affected by the accumulated noise to that span of $n_1 + \ldots + n_k$. Therefore, the nonlinear phase shift ϕ_{NL} **18** has a noisy component.

Fig. 2 shows a complex scattergram pattern, referred to with a reference **25**, of a baseband representation of a received optical BPSK signal in the "1" state transmitted as $E_0 = +A$. The pattern **25** is plotted with 5000 noise simulation points. Each instance of the simulated complex field is graphed in the scattergram pattern **25** with real part as the x-axis **12** and imaginary part as the y-axis **13**, and is represented as a single point according to the formula $E_N \exp(j\phi_{NL} - j\langle\phi_{NL}\rangle)$ which is equal to $E_R \exp(-j\langle\phi_{NL}\rangle)$ with a mean nonlinear phase shift $\langle\phi_{NL}\rangle$ of about 1 radian taken out. The points of the scattergram pattern **25** are similar to the end of the vector of **20** where the whole figure is rotated by minus the angle of the mean nonlinear phase shift $\langle\phi_{NL}\rangle$. The scattergram pattern **25** shows a random scattering of the simulation points due to contamination by the amplifier noise **16** and a shape having the appearance of a section of a helix due to the nonlinear phase shift of $\phi_{NL} - \langle\phi_{NL}\rangle$. Fig. 2 indicates that the rotation of the nonlinear phase shift of $\phi_{NL} - \langle\phi_{NL}\rangle$ is correlated to the distance from the origin **14**. In general, the farther the points are from the origin **14**, the more the rotation about the origin **14**.

Conventionally, as described widely in literature, the BPSK signal is detected by determining whether the signal is in the right or left of the y-axis **13**, for "1" and "0", respectively. A conventional detector viewed as a polar detector determines whether the absolute value of the received phase θ is less than $\pi/2$ for "1" or greater than $\pi/2$ for "0". A conventional detector viewed as a rectangular detector determines whether one of the quadrature components, cos(θ), is positive or negative for "1" or "0", respectively. In the conventional detectors, the intensity of the received signal need not be known in the detection process.

After taking out the mean $\langle\phi_{NL}\rangle$ of the nonlinear phase shift ϕ_{NL} **18**, Gordon and Mollenauer determine whether the signal is in the right or left of the y-axis **13** with the conventional phase detector. With the assumption of the conventional phase detector, Gordon and Mollenauer arrive at an estimation that the nonlinear phase shift mean $\langle\phi_{NL}\rangle$ should be about less than 1 radian. This requirement of mean nonlinear phase shift $\langle\phi_{NL}\rangle$ limits the transmission distance of an optical transmission system.

There is a need for a method and apparatus to overcome the interaction of optical amplifier noise and Kerr effect in order to extend transmission distance.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus in an optical system using an estimate of signal strength for reducing the effect of nonlinear phase noise induced by the interaction of amplifier noise and Kerr effect.

In a preferred embodiment, a receiver of the present invention includes a complex signal estimator and an intensity-scaled phase noise compensator. The complex signal estimator provides an estimate of the complex components of a received optical signal. The complex components may be in a polar form of phase and signal strength or a rectangular form of real and imaginary terms. The phase noise compensator uses signal strength for compensating for the nonlinear phase noise in the complex components in order to provide a phase noise compensated representation of the optical signal. In one variation the phase noise compensator includes a rotator for rotating the complex components by a scaled signal strength and a data detector using the rotated complex components for detecting modulation data. In another variation the phase noise compensator includes a curved region detector having curved regions. The curved regions have nonlinear decision boundaries based upon a scale factor. The curved region detector detects data by determining the region that encloses the complex components. The complex components and the signal strength may be differential between symbol periods.

In another preferred embodiment, a receiver of the present invention includes a frequency estimator and an intensity-scaled phase noise compensator. The phase noise compensator shifts an estimated frequency by a scaled signal strength for compensating for nonlinear phase noise in a received optical signal.

In another preferred embodiment, an intensity-scaled phase noise compensator of the present invention compensates for nonlinear phase noise phase by re-modulating an optical signal with a scaled signal strength.

The signal strength scale factor of the present invention is determined based upon the number of spans in an optical transmission system.

The present invention eliminates a portion of the Kerr effect phase noise that is due to the interaction of optical amplifier noise and Kerr effect. The variance of the residual nonlinear phase shift with correction is reduced to approximately one fourth of that of the variance of the received nonlinear phase shift without correction. The methods and apparatus of the present invention described herein can be used in an optical transmission system to approximately double the transmission distance by doubling the number of spans by allowing the transmission system to accumulate about twice the mean nonlinear phase if the noisy nonlinear phase shift is the dominant degradation. Alternatively, the lengths of the spans can be increased. For a fiber loss coefficient of 0.20 dB/km the lengths of the spans can be increased by about 15 kilometers by doubling the launched power per span.

Various preferred embodiments of the present invention will now be described in detail with reference to the accompanying drawings, which are provided as illustrative examples.

IN THE DRAWINGS

Fig. 1 is a vector diagram of the prior art illustrating the effect of optical amplifier noise and nonlinear Kerr effect phase shift in a phase-modulated system;

Fig. 2 is a scattergram of the prior art illustrating the nonlinear phase noise that is generated by the interaction of optical amplifier noise and Kerr effect in a phase-modulated system;

Fig. 3 is a scattergram illustrating the effect of the compensation of the present invention for reducing the nonlinear phase noise of Fig. 2;

Fig. 4 is a block diagram of a receiver of the present invention having a phase estimator and an intensity-scaled phase noise compensator;

Fig. 5 is a block diagram of a receiver of the present invention having quadrature estimator and an intensity-scaled phase noise compensator;

Fig. 6 is an illustration showing a nonlinear decision boundary of the present invention;

Fig. 7 is a block diagram of a receiver of the present invention having a phase detector and an intensity-scaled nonlinear phase noise compensator using the nonlinear decision boundary of Fig. 6;

Fig. 8 is a block diagram of a receiver of the present invention having a quadrature estimator and an intensity-scaled phase noise compensator using the nonlinear decision boundary of Fig. 6;

Fig. 9 is a block diagram of a receiver of the present invention having a differential phase estimator and an intensity-scaled phase noise compensator;

Fig. 10 is a block diagram of a receiver of the present invention having a differential quadrature estimator and an intensity-scaled phase noise compensator;

Fig. 11 is a block diagram of a receiver of the present invention having a differential frequency estimator and an intensity-scaled phase noise compensator;

Fig. 12 is an exemplary detailed block diagram a quadrature estimator of a receiver of the present invention;

Fig. 13 is an exemplary detailed block diagram of a differential quadrature estimator of a receiver of the present invention; and

Fig. 14 is a block diagram of an intensity-scaled phase noise compensator of the present invention using a phase modulator.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a method and apparatus for detecting phase modulated data of the received optical signal of an optical transmission system where the received phase is contaminated by the nonlinear phase noise induced by the interaction optical amplifier noise and Kerr effect of an optical fiber. The method and apparatus use the idea that the nonlinear phase shift **18** (Fig. 1) is correlated with the intensity of the received signal related to the lengths of vectors **17, 20** (Fig. 1). The present invention is based on the idea that the nonlinear phase shift is correlated with the received intensity. While both the nonlinear phase shift and the received intensity have noisy components, those noisy components are correlated and we use one to partially cancel another.

The correlation is more obvious in a brief mathematical explanation given below for illustrative purposes. For the simple example of two fiber spans, the received electric field signal is $E_2 = E_0 + n_1 + n_2$ and the nonlinear phase shift is $\phi_{NL} = -\gamma L_{eff}\left(|E_0 + n_1|^2 + |E_0 + n_1 + n_2|^2\right)$. The conventional method, which detects the phase according to the received electric field $E_2\exp(j\phi_{NL})$, gives a phase of $\phi_2 = \theta_2 + \phi_{NL} = \theta_2 - \gamma L_{eff}\left(|E_0 + n_1|^2 + |E_0 + n_1 + n_2|^2\right)$, where θ_2 is the phase of E_2. Because the received signal intensity is $P_2 = |E_0 + n_1 + n_2|^2$, the effects of nonlinear phase shift can be reduced by estimating the phase by $\phi_2 + \gamma L_{eff} P_2 = \theta_2 - \gamma L_{eff}|E_0 + n_1|^2$ by adding a correction term of $\gamma L_{eff} P_2$ into the estimated phase of the received signal of $E_2\exp(j\phi_{NL})$. The effects of nonlinear phase shift can be reduced further because the remaining nonlinear phase shift of $-\gamma L_{eff}|E_0 + n_1|^2$ is still correlated with the intensity $P_2 = |E_0 + n_1 + n_2|^2$. As shown later, the optimal correction term for two spans is about $1.5\gamma L_{eff} P_2$.

For the general case of an optical transmission system with N spans, mathematically the optimal way to add a correction term is to find an optimal scale factor α to minimize the variance of the residual nonlinear phase shift $\phi_{NL} + \alpha P_N$, where $P_N = |E_N|^2 = |E_0 + n_1 + \ldots + n_N|^2$ is the received signal intensity at the receiver. After some algebra, the optimal factor is α, is shown in an equation 2 below. The approximation in the equation 2 is valid for high signal-to-noise ratio.

$$\alpha = \gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2} \approx \gamma L_{\text{eff}} \frac{N+1}{2} \quad (2)$$

Fig. 3 shows a complex scattergram pattern **30** for the present invention. The scattergram pattern **30** is a baseband representation of a received optical BPSK signal in the "1" state transmitted as $E_0 = +A$. The pattern **30** is generated from 5000 simulation points for different noise combinations having nonlinear phase compensation according to the present invention. Each instance of the simulated complex field is graphed with real part as the x-axis **12** and imaginary part as the y-axis **13**, and is represented as a single complex point according to the formula $E_c = E_N \exp(j(\phi_{NL} + \alpha P_N) - j\langle\phi_{NL}\rangle - j\alpha\langle P_N\rangle)$ as the electrical field after correction with residual nonlinear phase shift of $\phi_{NL} + \alpha P_N$ with the mean taken out.

For the typical case with small noise, the mean nonlinear phase shift $\langle\phi_{NL}\rangle$ is about $N\gamma L_{\text{eff}}|E_0|^2$ and a mean received power of about $|E_0|^2$, the optimal scale factor α for large number N of fiber spans is about 50% of the ratio of mean nonlinear phase shift $\langle\phi_{NL}\rangle$ and the mean received power $|E_0|^2$. As compared with the helix shaped scattergram pattern **25** of the prior art, the roughly round shape of the scattergram pattern **30** shows that the effect of the nonlinear phase shift **18** has been reduced. Comparing the prior art scattergram pattern **25** and the present invention scattergram pattern **30**, the effect of nonlinear phase shift ϕ_{NL} **18** is reduced dramatically by using the correction term of αP_N. It should be noted, however, that the effect of the nonlinear phase shift ϕ_{NL} **18** is not entirely eliminated in the present invention.

The parameter that can be used to characterize the effect of phase correction is to compare the variance of $\text{var}(\phi_{NL} + \alpha P_N)$ for residual nonlinear phase shift with the variance of $\text{var}(\phi_{NL})$ for the original nonlinear phase shift. As a good approximation for large optical signal-to-noise ratio and large number N of fiber spans, the ratio of $\text{var}(\phi_{NL} + \alpha P_N)/\text{var}(\phi_{NL})$ is about ¼, giving a reduction of about 50% in terms of standard deviation. Typically, the mean nonlinear phase shift $\langle\phi_{NL}\rangle$ is approximately equal to $N\gamma L_{\text{eff}}|E_0|^2$, the variance of nonlinear phase shift $\text{var}(\phi_{NL})$ is approximately equal to $4N^3(\gamma L_{\text{eff}}\sigma|E_0|)^2/3$, and the variance of residual nonlinear phase shift $\text{var}(\phi_{NL} + \alpha P_N)$ is approximately equal to $N^3(\gamma L_{\text{eff}}\sigma|E_0|)^2/3$. With a given signal-to-noise ratio at the receiver, the variance of nonlinear phase shift var(ϕ_{NL}) is approximately equal to $2<\phi_{NL}>^2/(3\text{SNR})$ and the variance of residual nonlinear phase shift var($\phi_{NL} + \alpha P_N$) is approximately equal to $<\phi_{NL}>^2/(6\text{SNR})$, where $\text{SNR} = |E_0|^2/(2N\sigma^2)$ is the signal-to-noise ratio (SNR). As the standard deviation of nonlinear phase shift is proportional to the mean nonlinear phase shift $<\phi_{NL}>$, we can conclude that the system with the correction of nonlinear phase shift can allow twice the mean nonlinear phase shift $<\phi_{NL}>$, which corresponds to doubling the transmitted distance by doubling the number N of fiber spans.

The above description assumes that the launched power in each span is identical, the fiber in each span has the same length, and the optical amplifier noise in each span has the same statistical properties. For a more general system, the optimal scale factor α is equal to about 50% of the ratio of mean nonlinear phase shift and received power. The above description also assumes that the received signal is equal to the optical signal entering the last span. If the received signal after the last span is amplified using an optical amplifier with optical amplifier noise before the receiver, assume that the received power is equal to the launched power per span, the above discussion is still valid by changing N to $N+1$ for the equation 2 with one more amplifier. In the above model, with the optimal correction term αP_N, the last span does not introduce nonlinear phase shift ϕ_{NL}. Equivalently, an optical amplifier before the receiver also does not introduce nonlinear phase shift ϕ_{NL}. The importance of the current invention is that the use of the correction term of αP_N reduces the effect of nonlinear phase shift ϕ_{NL} **18**. The present invention can be implemented by using various methods and apparatus.

The term "complex components" is used herein to mean a phase and a (positive) signal strength in a polar coordinate system or two signal (positive or negative) components in a rectangular coordinate system. The two components in the rectangular coordinate system are typically real and imaginary quadrature components or in-phase and quadrature-phase parts of the signal. However, the two components can be any two components that are not phase coincident. The "signal strength" of a signal may be in units of power or magnitude where magnitude is the positive square root of power. Information may be converted back and forth between units of power and magnitude with conventional circuit or software techniques. The complex components and the signal strength may represent a signal during a certain time or may represent a difference in the signal between two times as in a differential phase, differential quadrature components, or differential signal strength.

Fig. 4 is a block diagram of a receiver of a preferred embodiment of the present invention referred to by a reference identifier **10A**. The receiver **10A** receives the optical signal E_R **42** and provides a nonlinear compensated phase, denoted by **43**, having a reduced level of unwanted nonlinear phase noise. The compensated phase **43**, shown below as $\hat{\phi}_R + \alpha\hat{P}_N$, is a phase noise compensated representation of the received optical signal E_R **42**.

The receiver **10A** includes a complex signal estimator **45** for receiving the optical signal E_R **42** and an intensity-scaled phase noise compensator **47** for providing detected data **48**. The complex signal estimator **45** includes a phase estimator **50** and a signal strength estimator **51**. The phase estimator **50** estimates the actual phase ϕ_R of the optical signal E_R **42** for providing an estimated phase $\hat{\phi}_R$ **55**. The phase $\hat{\phi}_R$ **55** is preferably the estimated difference between the phase ϕ_R of the optical signal E_R **42** and a mean $<\phi_R>$ of that phase. The signal strength estimator **51** estimates the actual power $P_N = |E_N|^2 = |E_R|^2$ in the received optical signal E_R **42** for providing an estimated power $\hat{P}_N$ **56**. Preferably, the power $\hat{P}_N$ **56** is the estimated difference between the power P_N of the optical signal E_R **42** and a mean $<P_N>$ of that power.

The phase noise compensator **47** includes a scaler **57**, a phase rotator **58**, and a polar data detector **59**. Information for the scale factor α is stored by the scaler **57**. The scaler **57** multiplies the estimated power $\hat{P}_N$ **56** by the scale factor α and passes the estimated phase $\hat{\phi}_R$ and a scaled signal strength $\alpha\hat{P}_N$ to the phase rotator **58**. The phase rotator **58** adds the scaled signal strength $\alpha\hat{P}_N$ to the phase $\hat{\phi}_R$ in order to rotate the phase $\hat{\phi}_R$ by $\alpha\hat{P}_N$. The rotated phase $\hat{\phi}_R + \alpha\hat{P}_N$ is the nonlinear compensated phase **43**. The polar data detector **59** uses the nonlinear compensated phase $\hat{\phi}_R + \alpha\hat{P}_N$ **43** for detecting the modulated data that is carried on the optical signal E_R **42** and issuing the estimate as the detected data **48**.

For BPSK modulation, the polar data detector **59** uses $\pi/2$ as a decision boundary. While the current invention and all previous prior arts can be generalized to more complicated phase-modulated system, or its variations combined with amplitude and/or frequency modulation, we use BPSK system as our preferred example. In the simple case of BPSK, the polar data detector **59** makes the decision whether "1" or "0" is transmitted by the criterion of whether the absolute value of the compensated phase **43** is less than $\pi/2$ for "1" or greater than $\pi/2$ for "0". The polar detector **59** may require other information to make a decision if the original data is not only phase modulated, but also encoded in amplitude or frequency.

The signal strength estimator **51** and the phase estimator **50** may be implemented as two separate blocks or combined into a single circuit or block. In some literature, the nonlinear phase shift ϕ_{NL} **18** is described as a positive phase shift. The scale factor α is negative in the specific case in which the nonlinear phase shift is regarded as being a positive phase shift.

Fig. 5 is a block diagram of a receiver of another preferred embodiment of the present invention referred to by a reference identifier **10B**. The receiver **10B** receives the optical signal E_R **42** and provides nonlinear phase noise compensated quadrature components $\hat{x}_c$ and $\hat{y}_c$, denoted by **72**, having a reduced level of unwanted nonlinear phase noise. The phase noise compensated quadrature components $\hat{x}_c$ and $\hat{y}_c$ **72** are a phase noise compensated representation of the received optical signal E_R **42**.

The receiver **10B** includes a complex signal estimator **73** for receiving the electric field of the optical signal E_R **42** and an intensity-scaled phase noise compensator **74** for providing the detected data **48**. The complex signal estimator **73** includes a quadrature estimator **75**. The quadrature estimator **75** estimates of the actual quadrature components x_R and y_R of the optical signal E_R **42** for providing estimated quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80**. The phase noise compensator **74** includes a signal strength estimator **76**. The signal strength estimator **76** uses the quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80** for estimating power of the received signal E_R **42** to provide an estimated power $\hat{P}_N = \hat{x}_R^2 + \hat{y}_R^2$, denoted by **81**. In an alternative embodiment the signal strength estimator **76** determines the estimated power $\hat{P}_N$ directly from the optical signal E_R **42**.

The phase noise compensator **74** also includes a scaler **82**, a quadrature rotator **83**, and a rectangular data detector **85**. Information for the scale factor α is stored by the scaler **82**. The scaler **82** multiplies the power $\hat{P}_N$ **81** by the scale factor α and passes the quadrature components $\hat{x}_R$ and $\hat{y}_R$ and a scaled signal strength $\alpha\hat{P}_N$ to the quadrature rotator **83**. The quadrature rotator **83** rotates the quadrature estimates $\hat{x}_R$ and $\hat{y}_R$ by the scaled signal strength $\alpha\hat{P}_N$ according to an equation 3, below, for providing the nonlinear phase noise compensated quadrature components $\hat{x}_c$ and $\hat{y}_c$ **72**.

$$\begin{aligned}\hat{x}_c &= \hat{x}_R\cos(\alpha\hat{P}_N) - \hat{y}_R\sin(\alpha\hat{P}_N)\\ \hat{y}_c &= \hat{x}_R\sin(\alpha\hat{P}_N) + \hat{y}_R\cos(\alpha\hat{P}_N)\end{aligned} \qquad (3)$$

The rectangular data detector **85** uses the phase noise compensated quadrature components $\hat{x}_c$ and $\hat{y}_c$ **72** for providing the detected data **48** that is representative of the original encoded or modulated data that is carried on the optical signal E_R **42**.

In the simple case of BPSK, the rectangular data detector **85** makes the decision whether "1" or "0" is transmitted by the criterion whether one of the quadrature components $\hat{x}_c$ of the compensated phase representation **72** is positive or negative, respectively. In the case of phase and amplitude modulation called quadrature-amplitude modulation (QAM) or the case of *M*-ary phase-shift keying (MPSK), both quadrature components of $\hat{x}_c$ and $\hat{y}_c$ **72** are required for the detector **85** to provide the detection data **48**. The rectangular data detector **85** can be implemented as a traditional quadrature detector for the specific modulation technique.

Fig. 6 shows an optimal nonlinear decision boundary **91** separating received signal-space into curved regions **92** and **94**. The region **92** containing the signal point of "1" is the decision region to determine when "1" is transmitted. The region **94** containing the signal point of "0" is the decision region to determine when "0" is transmitted. The curved regions **92** and **94** can be used for detecting the data **48** from the estimated quadrature components of $\hat{x}_R$ and $\hat{y}_R$ **80** (Fig. 5). The boundary **91** has a rotation angle for a mean nonlinear phase shift $\langle\phi_{NL}\rangle$. However, in order to make the idea of the present invention easier to understand, the boundary **91** and the signal points "1" and "0" are plotted without showing this rotation. If the mean nonlinear phase shift $<\phi_{NL}>$ were shown, the boundary **91** and the signal points "1" and "0" would be rotated by the angle $<\phi_{NL}>$.

After taking away the constant nonlinear phase shift of $<\phi_{NL}>$, for a BPSK system, the decision region **92** for "1" is $\hat{x}_R \sin[\alpha(\hat{x}_R^2 + \hat{y}_R^2)] + \hat{y}_R \cos[\alpha(\hat{x}_R^2 + \hat{y}_R^2)] \geq 0$ and the decision region **94** for "0" is $\hat{x}_R \sin[\alpha(\hat{x}_R^2 + \hat{y}_R^2)] + \hat{y}_R \cos[\alpha(\hat{x}_R^2 + \hat{y}_R^2)] < 0$. The decision regions **92** and **94** can also be expressed in polar coordinates. In polar coordinates the decision region **92** for "1" is $\left|\hat{\phi}_R + \alpha\hat{\rho}_R^2\right| \leq \pi/2$ and the decision region **94** for "0" is $\left|\hat{\phi}_R + \alpha\hat{\rho}_R^2\right| > \pi/2$, where $\hat{\rho}_R = (\hat{y}_R^2 + \hat{x}_R^2)^{1/2}$ and $\hat{\phi}_R = \tan^{-1}(\hat{y}_R / \hat{x}_R)$ is the polar coordinate representation of the rectangular representation of $\hat{x}_R$ and $\hat{y}_R$.

The optimal shape of the boundary **91** depends upon the scale factor α. The boundary **91** is drawn for an optical transmission system using BPSK modulation and having a mean nonlinear phase shift $<\phi_{NL}>$ of about 1 radian. In the case of mean nonlinear phase shift $<\phi_{NL}> = 0$, the boundary **91** becomes, in rectangular coordinates, the y-axis **13**. In polar coordinates, the boundary **91** is $\phi + \alpha\rho^2 = 0$, where $\rho > 0$ is the radius and ϕ is the angle.

For QAM or MPSK modulation, instead of the single boundary curve **91** to separate the entire complex space into two decision regions, there are multiple curves to separate the complex space into *M* decision regions, where *M* is the number of constellation points in the modulation scheme. For MPSK, the curves that separate the *M* decision regions are the rotated version of the curve of $\phi + \alpha \rho^2 = 0$. For QAM, the curves that separated the *M* decision regions are the rotated version of a family of curves defined by $\rho\sin(\phi + \alpha \rho^2) = \beta$, where β is a constant to define different curve. The special case of $\beta = 0$ is the curve of $\phi + \alpha \rho^2 = 0$. For example, for 16-QAM modulation with 16 constellation points in a square arrangement, the decision regions are separated by the rotated versions of two curves of $\phi + \alpha \rho^2 = 0$ and $\rho\sin(\phi + \alpha \rho^2) = \beta_1$, where β_1 is a constant.

In practice, the curved regions **92** and **94** touching at the decision boundary **91** can be implemented using a look-up table. The look-up table can be implemented for either complex quadrature components $\hat{x}_R$ and $\hat{y}_R$ or magnitude and phase components of $\hat{\rho}_R$ and

$\hat{\phi}_R$, where $\hat{\rho}_R$ corresponds to the radius ρ. The magnitude $\hat{\rho}_R$ is the square root of $\hat{P}_N$. As the magnitude $\hat{\rho}_R$ is always positive in our case, the look-up table can also be implemented using the estimated power and phase of the received signal of $\hat{P}_N = \hat{\rho}_R^2$ and $\hat{\phi}_R$, respectively, by a simple one-to-one mapping.

Fig. 7 is a block diagram of a receiver of the present invention referred to by a reference identifier **10C**. The receiver **10C** receives the optical signal E_R **42** and uses one or more of the nonlinear decision boundary curves **91** (Fig. 6) with the estimated quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80** for providing detected data **48** having a reduced level of unwanted nonlinear phase noise. The detected data **48** is a nonlinear phase noise compensated representation of the optical signal E_R **42**.

The receiver **10C** receives the optical signal E_R **42** and uses one or more of the nonlinear decision boundary curves **91** (Fig. 6) with the estimated quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80** for providing detected data **48** having a reduced level of unwanted nonlinear phase noise. The detected data **48** is a nonlinear phase noise compensated representation of the optical signal E_R **42**.

The receiver **10C** includes the quadrature estimator **75** and a phase noise compensator **108**. The quadrature estimator **75** receives the optical signal E_R **42** and provides the estimated quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80**. The phase noise compensator **108** includes a rectangular curved region detector **110** having stored information for the curved regions **92** and **94**. The region detector **110** issues the detected data **48** according to which particular one of the curved regions **92** and **94** encloses the complex location of the quadrature components $\hat{x}_R$ and $\hat{y}_R$ **80**.

Fig. 8 is a block diagram of a receiver of the present invention referred to by a reference identifier **10D**. The receiver **10D** receives the optical signal E_R **42** and uses one or more of the nonlinear decision boundary curves **91** (Fig. 6) with the estimated polar coordinates $\hat{\phi}_R$ **55** and power $\hat{P}_N$ **56** for providing detected data **48** having a reduced level of unwanted nonlinear phase noise. The detected data **48** is a nonlinear phase noise compensated representation of the optical signal E_R **42**.

The receiver **10D** includes a complex signal estimator **116** and a nonlinear phase noise compensator **118**. The complex signal estimator **116** includes the phase estimator **50** for receiving the optical signal E_R **42** and providing the estimated phase $\hat{\phi}_R$ **55** and the signal strength estimator **51** for receiving the optical signal E_R **42** and providing the estimated power $\hat{P}_N$ **56**.

The phase noise compensator **118** includes a polar curved region detector **120** having stored information for the curved regions **92** and **94**. The region detector **120** issues the detected data **48** according to which particular one of the curved regions **92** and **94** encloses the complex location of the power $\hat{P}_N$ **56**, corresponding to radius ρ^2, and the phase $\hat{\phi}_R$ **55**.

The region detectors **108** and **118** can be implemented with look-up tables. Several look-up tables may be included where each table corresponds to curved regions, analogous to the curved regions **92** and **94**, for different scale factors α for different levels, respectively, of the mean nonlinear phase $\langle\phi_{NL}\rangle$.

Fig. 9 is a block diagram of a receiver of another preferred embodiment of the present invention referred to by a reference identifier **10E**. The receiver **10E** receives the optical signal E_R **42** and provides a differential nonlinear compensated phase, denoted by **152**, having a reduced level of unwanted nonlinear phase noise. The compensated phase **152**, shown below as $\Delta\hat{\phi}_R + \alpha\Delta\hat{P}_N$, is a nonlinear phase noise compensated representation of the optical signal E_R **42**.

The receiver **10E** is intended for a differential phase-shifted keyed (DPSK) system. DPSK systems use the difference of the phase between two adjacent transmitted symbols to encode data. In DPSK systems, the data is encoded or modulated in $\phi(t+T) - \phi(t)$ of the carrier, where t is time and T is the symbol interval. As in a DPSK system, as in a BPSK system, the nonlinear phase shift due to the interaction of optical amplifier noise and Kerr effect degrades performance. Conventionally, the data is decoded using $\phi_R(t+T) - \phi_R(t)$ without using the information from the received intensity. In a DPSK system, the difference in nonlinear phase shift $\phi_{NL}(t+T) - \phi_{NL}(t)$ is also correlated with the difference in received intensity $P_N(t+T) - P_N(t)$ with the same correlation as that for BPSK system. A detector making decisions according to $\phi_R(t+T) - \phi_R(t) + \alpha[P_N(t+T) - P_N(t)]$ can be used to reduce the effect of nonlinear phase shift. The optimal combining factor α for DPSK system is the same as that for BPSK system.

The receiver **10E** includes a complex signal estimator **153** for receiving the optical signal E_R **42** and an intensity-scaled phase noise compensator **154** for providing the detected data **48**. The complex signal estimator **153** includes a differential phase estimator **160** and a differential signal strength estimator **161**. The differential phase estimator **160** estimates the differential phase $\Delta\phi_R = \phi_R(t+T) - \phi_R(t)$ of the optical signal E_R **42** for providing an estimated differential phase $\Delta\hat{\phi}_R$, denoted with a reference identifier **170**, corresponding to the difference between the phase $\phi_R(t)$ at a time t and the phase $\phi_R(t+T)$ at a time $t+T$, where T is a symbol time period. The signal strength estimator **161** estimates the differential power $\Delta P_N = P_N(t+T) - P_N(t)$ for providing an estimated differential power $\Delta\hat{P}_N$, denoted by **171**, where $P_N = |E_N|^2 = |E_R|^2$.

The phase noise compensator **154** includes the scaler **57**, the phase rotator **58**, and the polar data detector **59** operating on the differential phase $\Delta\hat{\phi}_R$ **170** and the differential power **171** in the manner as described above in the detailed description accompanying Fig. 4 for the phase $\hat{\phi}_R$ **55** and the power $\hat{P}_N$ **56**. Information for the scale factor α is stored by the scaler **57**. The scaler **57** multiplies the differential power $\Delta\hat{P}_N$ **171** by the scale factor α and passes the differential phase $\Delta\hat{\phi}_R$ and a scaled differential power $\alpha\Delta\hat{P}_N$ to the phase rotator **58**. The phase rotator **58** adds the differential phase $\Delta\hat{\phi}_R$ and the scaled differential power $\alpha\Delta\hat{P}_N$ in order to rotate the differential phase $\Delta\hat{\phi}_R$ by the scaled differential signal strength $\alpha\Delta\hat{P}_N$. The rotated differential phase $\Delta\hat{\phi}_R + \alpha\Delta\hat{P}_N$ is the differential nonlinear compensated phase **152** of the received optical signal E_R **42**. The polar data detector **59** uses the differential nonlinear compensated phase $\Delta\hat{\phi}_R + \alpha\Delta\hat{P}_N$ **152** for providing the detected data **48**. For binary DPSK modulation, the polar data detector **59** uses $\pi/2$ as a decision boundary, i.e., the decision is made based on whether the absolute value of the differential nonlinear compensated phase is less than or greater than $\pi/2$.

Fig. 10 is a block diagram of a receiver of another preferred embodiment of the present invention referred to by a reference identifier **10F**. The receiver **10F** receives the optical signal E_R **42** and provides nonlinear phase noise compensated differential quadrature components $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$, denoted by **182**, having a reduced level of unwanted nonlinear phase noise. The compensated differential quadrature components $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ **182** are a nonlinear phase noise compensated representation of the optical signal E_R **42**.

The receiver **10F** includes a complex signal estimator **183** for receiving the optical signal E_R **42** and an intensity-scaled nonlinear phase noise compensator **184** for providing the detected data **48**. The complex signal estimator **183** includes a differential quadrature estimator **190** and the differential signal strength estimator **161**. The differential quadrature estimator **190** receives the electric field of E_R **42** and estimates differential quadrature components $\Delta x_R = |E_R|\cos\Delta\phi_R$ and $\Delta y_R = |E_R|\sin\Delta\phi_R$ of the optical signal E_R **42** for providing differential quadrature component estimates $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$, denoted with a reference identifier **191**, corresponding to the quadrature components of the differential phase of $\Delta\phi_R = \phi_R(t+T) - \phi_R(t)$. The differential signal strength estimator **161** receives the optical signal E_R **42** and provides the estimated differential power $\Delta\hat{P}_N$ **171** that is the estimation of the actual differential power $\Delta P_N = P_N(t+T) - P_N(t)$.

The phase noise compensator **184** includes the scaler **82**, the quadrature rotator **83**, and the rectangular data detector **85**. Information for the scale factor α is stored by the scaler **82**. The scaler **82** multiplies the differential power $\Delta\hat{P}_N$ **171** by the scale factor α and passes the differential quadrature components $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ and a scaled differential power $\alpha\Delta\hat{P}_N$ to the quadrature rotator **83**. The quadrature rotator **83** rotates the differential quadrature estimates $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ according to an equation 4, below, for providing rotated differential quadrature component estimates $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ as the compensated phase **182**.

$$\begin{aligned}\Delta\hat{x}_c &= \Delta\hat{x}_R\cos(\alpha\Delta\hat{P}_N) - \Delta\hat{y}_R\sin(\alpha\Delta\hat{P}_N)\\ \Delta\hat{y}_c &= \Delta\hat{x}_R\sin(\alpha\hat{P}_N) + \Delta\hat{y}_R\cos(\alpha\Delta\hat{P}_N)\end{aligned} \qquad (4)$$

The rectangular data detector **85** uses the rotated quadrature components of $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ **182** for providing the detected data **48**.

Fig. 11 is a block diagram of a receiver of another preferred embodiment of the present invention referred to by a reference identifier **200**. The receiver **200** receives the optical signal E_R **42** and provides a nonlinear phase noise compensated frequency, denoted by **202**, having a reduced level of unwanted nonlinear phase noise. The phase noise compensated frequency **202**, shown below as $\Delta f + \alpha\Delta\hat{P}_N / T$, is a phase noise compensated representation of the optical signal E_R **42**.

Some optical communication systems use frequency to encode data, a technique referred to as frequency-shifted keying (FSK). In an FSK system, the data is encoded or modulated into the frequency that is equal to dϕ(t)/dt where d/dt denotes differentiation operation with respect to time. There are many different types of frequency estimators, most of them estimating the difference a carrier frequency and a frequency in a time interval between a time t_0 and a time $t_0 + T$, where the time T is a symbol time period. Usually, the output of a differential frequency estimator is proportional to a differential frequency $\Delta f = \hat{f}(t_0 + T) - \hat{f}(t_0)$, where $\hat{f}(t_0 + T)$ is the estimated frequency at $t_0 + T$, $\hat{f}(t_0)$ is the estimated frequency at t_0. The nonlinear phase noise correction to the differential frequency is $\alpha[P_N(t_0+T) - P_N(t_0)]/T$. The optimal scale factor α for FSK is the scale factor α that is optimum for a BPSK system.

The receiver **200** includes a differential frequency estimator **210**; the differential signal strength estimator **161** for receiving the optical signal E_R **42**; and an intensity-scaled phase noise compensator **212** for providing the detected data **48**. The frequency estimator **210** receives the optical signal E_R **42** and estimates the differential frequency that encoded the transmitted data for providing the estimated differential frequency Δf described above and denoted as **215**. The differential signal strength estimator **161** receives the optical signal E_R **42** and provides information for the estimated differential power $\Delta\hat{P}_N$ **171** as described above.

The phase noise compensator **212** includes a scaler **218**, a frequency shifter **222**, and a frequency data detector **224**. Information for the scale factor α is stored by the scaler **218**. The scaler **218** multiplies the differential power $\Delta\hat{P}_N$ **171** by the scale factor α and divides by the symbol time period T for providing a scaled differential power $\alpha\,\Delta\hat{P}_N/T$ and passes the differential frequency Δf and the scaled differential power $\alpha\,\Delta\hat{P}_N/T$ to the frequency shifter **222**. The frequency shifter **222** adds the Δf and $\alpha\,\Delta\hat{P}_N/T$ provided by the scaler **218** in order to shift the frequency Δf by the scaled differential power $\alpha\,\Delta\hat{P}_N/T$. The shifted frequency $\Delta f + \alpha\,\Delta\hat{P}_N/T$ is the nonlinear phase noise compensated frequency **202** of the received optical signal E_R **42**. In the simple case of binary FSK, the detector makes the decision whether "1" or "0" is transmitted by the criterion whether the shifted frequency **202** is positive or negative. The frequency data detector **224** uses the shifted frequency **202** for detecting the modulated data that is carried on the optical signal E_R **42** and issuing the estimate as the detected data **48**.

Fig. 12 is a block diagram of a detailed exemplary implementation of the complex signal estimator **73** illustrated in Fig. 5 for the receiver **10B**. The complex signal estimator **73** includes the quadrature estimator **75** and the signal strength estimator **76**.

The quadrature estimator **75** is implemented as a phase-locked homodyne receiver. A local oscillator **252** is a light source with an output E_{lo} **253**. When the local oscillator **252** is locked into the received signal **42**, the optical frequency and phase of local oscillator output **253** is the same as that of the phase and carrier frequency of the received signal E_R **42**. In a practical implementation, a homodyne receiver typically includes some means to match the polarizations of the received optical electric field E_R **42** and the local oscillator optical electric field E_{lo} **253**, but this polarization-matching means is omitted from Fig. 12 for simplicity.

A passive optical hybrid **254** combines the received optical signal E_R **42** and the local oscillator field E_{lo} **253** and gives four outputs, numbered **255**, **256**, **257**, and **258**, that are $\pi/2$ (90°) apart in phase. The four outputs are the zero-phase output of $(E_R+E_{lo})/2$ **255**, the π-phase output of $(E_R-E_{lo})/2$ **256**, the $\pi/2$-phase output of $(E_R+jE_{lo})/2$ **257**, and the $-\pi/2$-phase output of $(E_R-jE_{lo})/2$ **258**. Four photodetectors, numbered **260**, **261**, **262**, and **263**, are used to convert the combined optical signal of optical hybrid outputs **255**, **256**, **257**, and **258**, respectively, to four photocurrents, numbered **264**, **265**, **266**, and **267**. The zero- and π-phase photocurrents, numbered **264** and **265**, respectively, are fed into a subtraction device **270**. The $\pi/2$- and $-\pi/2$-phase photocurrents, numbered **266** and **267**, respectively, are fed into a subtraction device **271**. Outputs **272** and **273** of the subtraction device **270** and **271**, respectively, are estimations of the quadrature components of the received optical signal E_R **42**. As both outputs **272** and **273** include wide-band electrical noise and are weak photocurrent, preamplifiers and low-pass filters, numbered **274** and **275**, are used to amplify the signal and filter the high-frequency noise. An output **80a** of preamplifier and low-pass filter **274** is the in-phase component estimate $\hat{x}_R$. An output **80b** of preamplifier and low-pass filter **275** is the quadrature-phase estimate $\hat{y}_R$. A loop filter **276** uses one of the quadrature components, in this case, the quadrature-phase quadrature component $\hat{y}_R$ **80b** to give a control signal **277** to local oscillator **252**. Using the control signal **277**, the output **253** of local oscillator **252** is locked into the phase and frequency of the received optical signal E_R **42**. The output $\hat{x}_R$ **80a** and the output $\hat{y}_R$ **80b** are issued as the quadrature components **80** and provided to the signal strength estimator **76**.

The signal strength estimator **76** uses quadrature components $\hat{x}_R$ and $\hat{y}_R$ denoted by **80a** and **80b** to estimate the received power and gives the estimated power output **81** of $\hat{P}_N = \hat{x}_R^2 + \hat{y}_R^2$. Two squaring devices, numbered **280** and **281**, give the square of the two quadrature components of $\hat{x}_R^2$ **282** and $\hat{y}_R^2$ **283**, respectively. A summing device **284** adds the outputs **282** and **283** of the squaring devices **280** and **281**, respectively, and issues the power $\hat{P}_N = \hat{x}_R^2 + \hat{y}_R^2$ **81**.

Fig. 13 is block diagram of a detailed exemplary implementation of the complex signal estimator **183** illustrated in Fig. 10 for the receiver **10F**. The complex signal estimator **183** includes the differential quadrature estimator **190** and the differential signal strength estimator **161**

The differential quadrature estimator **190** is implemented as an interferometric receiver. The received signal E_R **42** is split into two outputs **304** and **305** using a splitter **306**. The splitting ratio of splitter **306** can be chosen such that the power of one output signal **304** is larger than that in another output signal **305**. The signal **304** is passed to the differential quadrature estimator **190**. The signal **305** is passed to the differential signal strength estimator **161**.

The differential quadrature component estimator **190** includes a splitter **310** for splitting the signal **304** into two equal-power outputs, numbered **311** and **312**. The two splitter outputs of **311** and **312** are fed to two different interferometers, numbered **315** and **316**, with different phase setting. Both interferometers **315** and **316** are Mach-Zehnder type interferometer that splits a signal into two branches, which propagate along paths of different path lengths and are recombined. The path length difference for the two interferometers **315** and **316** is approximately the symbol time T. The first interferometer **315** issues two output signals, numbered **320** and **321**, that are proportional to $E_R(t)+E_R(t\text{-}T)$ and $E_R(t)-E_R(t\text{-}T)$ as the zero- and π-phase, respectively. The second interferometer **316** issues two output signals, numbered **322** and **323**, that are proportional to $E_R(t)+jE_R(t\text{-}T)$ and $E_R(t)-jE_R(t\text{-}T)$ as the $\pi/2$- and $-\pi/2$-phase output, respectively. Four photo-detectors, numbered **325, 326, 327,** and **328,** are used to convert the optical signals **320, 321, 322,** and **323,** respectively, to four photocurrents, numbered **330, 331, 332, 333,** respectively. The zero- and π-phase photocurrents **330** and **331** are fed into a subtraction device **340** to get their difference as **341.** The $\pi/2$- and $-\pi/2$-phase photocurrents **332** and **333** are fed into a subtraction device **342** to get their difference as **343.**

The outputs **341** and **343** of the subtraction devices **340** and **342,** respectively, are estimations of the differential quadrature components. As both outputs of **341** and **343** have wide-band electrical noise and are weak photocurrent, preamplifiers and low-pass filters, numbered **345** and **346,** are used to amplify the signal and filter the high-frequency noise. An output **191a** of preamplifier and low-pass filter **345** is the in-phase differential estimate $\Delta\hat{x}_R$. The output **191b** of preamplifier and low-pass filter **346** is the quadrature-phase estimate $\Delta\hat{y}_R$. The outputs **191a** and **191b** taken together comprise the differential quadrature components denoted as **191** in Fig. 10. A controller **350** uses both components $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ **191a** and **191b** for providing a control signal **351** to interferometer **315** and another control signal **352** to interferometer **316.** The interferometers **315** and **316** use the control signals **351** and **352** to maintain the correct phase relationship.

The differential signal strength estimator **161** includes the signal strength estimator **51.** The signal strength estimator **51** includes a photo-detector **360** to estimate the intensity of the received signal E_R **42.** A photocurrent **361** from the photo-detector **360** is amplified and filtered using a preamplifier and low-pass filter **362.** An output **363** of the preamplifier and low-pass filter **362** is an estimation of the intensity of the received signal E_R **42**. The estimated power **363** is delayed by a symbol time of T by a delay device **364**. A subtraction device **366** subtracts the delayed estimated power **365** from the current estimated power **363** for providing the differential power **171**.

Fig. 14 is a block diagram an intensity-scaled phase noise compensator of the present invention referred to by a reference identifier **400**. The compensator **400** receives an optical signal E_R **42** and provides a nonlinear phase noise compensated output optical signal, denoted by **406**, having a reduced level of unwanted nonlinear phase noise. The output optical signal is a nonlinear phase noise compensated representation of the received optical signal E_R **42**.

The received optical signal E_R **42** is split into first and second input signals **401** and **402** using a splitter **403**. The splitting ratio of splitter **403** can be chosen such that the power of the first input signal **401** is larger than the power in the second input signal **402**. The first input signal **401** is fed into an optical phase modulator **405** to give the output optical signal **406**. The second input signal **402** is passed to an optical intensity scaler **408**. The optical intensity scaler **408** includes the signal strength estimator **51**, a multiplier **410**, information for the scale factor α, and a modulator driver **412**. The signal strength estimator **51**, preferably using a photodetector, a preamplifier and a low pass filter, estimates the power in the second input signal **402** for providing an estimated power **413**. The multiplier **414** multiplies the estimated power **413** by the scale factor α for providing a correction voltage **416**.

The correction voltage **416** is amplified by the modulator driver **412** to give a nonlinear phase noise compensation drive signal **418**. The drive signal **418** drives the phase modulator **405** to modulate the first input signal **401** for providing the output optical signal **406**. The output optical signal **406** is a nonlinear phase noise compensated representation of the received optical signal E_R **42.** The output optical signal **406** of the phase modulator **405** can be fed to a receiver for data detection or continue its propagation through spans of optical fiber. In a preferred embodiment the phase modulator **405** modulates phase at the frequency of the optical signal E_R **42**.

Although the present invention has been described in terms of the presently preferred embodiments, it is to be understood that such disclosure is not to be interpreted as limiting. Various alterations and modifications will no doubt become apparent to those skilled in the art after having read the above disclosure. Accordingly, it is intended that the appended claims be interpreted as covering all alterations and modifications as fall within the true spirit and scope of the present invention.

What is claimed is:

CLAIMS

1. An optical receiver for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

a complex signal estimator for estimating complex components representative of said optical signal; and

an intensity-scaled phase noise compensator using information for a signal strength of said optical signal for compensating for said phase noise in said complex components and providing a phase noise compensated representation of said optical signal.

2. The receiver of claim 1, wherein:

said phase noise is Kerr effect phase noise.

3. The receiver of claim 1, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

4. The receiver of claim 1, wherein:

said phase noise is induced by additive noise in said spans.

5. The receiver of claim 1, wherein:

the phase noise compensator uses information for a scale factor for scaling said signal strength in order to provide a scaled signal strength, said scaled signal strength used for compensating for said phase noise.

6. The receiver of claim 5, wherein:

said scale factor is a function of a number N of said spans.

7. The receiver of claim 5, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

8. The receiver of claim 5, wherein:

said scale factor is approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is a noise variance for one of said spans.

9. The receiver of claim 5, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean nonlinear phase shift due to Kerr effect.

10. The receiver of claim 1, wherein:

said optical signal carries data in a form of phase modulation; and

said phase noise compensated representation represents said phase modulation.

11. The receiver of claim 1, wherein:

said optical signal carries data in a form of phase and amplitude modulation; and

said phase noise compensated representation represents said phase and amplitude modulation.

12. The receiver of claim 1, wherein:

the receiver includes a signal strength estimator for estimating said signal strength of said optical signal; and

the phase noise compensator includes a scaler storing information for a scale factor and using said scale factor for scaling said signal strength, and a rotator for rotating said complex components by said scaled signal strength for providing said phase noise compensated representation of said optical signal.

13. The receiver of claim 12, wherein:

the phase noise compensator further includes a data detector using said phase noise compensated representation for detecting modulation data carried on said optical signal.

14. The receiver of claim 12, wherein:

the complex signal estimator further includes a phase estimator for estimating a phase of said optical signal; and

said rotator rotates said phase by said scaled signal strength for providing said phase noise compensated representation.

15. The receiver of claim 14, wherein:

said phase is a differential phase; and

said signal strength is a differential signal strength.

16. The receiver of claim 14, wherein:

said rotator rotates said phase by adding said scaled signal strength to said phase for providing said phase noise compensated phase representation.

17. The receiver of claim 12, wherein:

the complex signal estimator further includes a quadrature estimator for estimating quadrature components of said optical signal; and

said rotator rotates said quadrature components by said scaled signal strength for providing said phase noise compensated representation.

18. The receiver of claim 17, wherein:

said rotator rotates said quadrature components according to

$$\hat{x}_c = \hat{x}_R \cos(\alpha \hat{P}_N) - \hat{y}_R \sin(\alpha \hat{P}_N)$$
$$\hat{y}_c = \hat{x}_R \sin(\alpha \hat{P}_N) + \hat{y}_R \cos(\alpha \hat{P}_N)$$

where $\hat{x}_R$ and $\hat{y}_R$ are said quadrature components, $\hat{P}_N$ is said signal strength, α is said scale factor, and $\hat{x}_c$ and $\hat{y}_c$ are said phase noise compensated representation.

19. The receiver of claim 17, wherein:

said quadrature components are differential quadrature components; and said signal strength is a differential signal strength.

20. The receiver of claim 19, wherein:

said rotator rotates said differential quadrature components according to

$$\Delta\hat{x}_c = \Delta\hat{x}_R \cos(\alpha\Delta\hat{P}_N) - \Delta\hat{y}_R \sin(\alpha\Delta\hat{P}_N)$$
$$\Delta\hat{y}_c = \Delta\hat{x}_R \sin(\alpha\hat{P}_N) + \Delta\hat{y}_R \cos(\alpha\Delta\hat{P}_N)$$

where $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ are said differential quadrature components, $\Delta\hat{P}_N$ is said differential signal strength, α is said scale factor, and $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ are said phase noise compensated representation.

21. The receiver of claim 1, wherein:

the phase noise compensator includes a curved region detector using one or more nonlinear decision boundaries for detecting data carried on said optical signal.

22. The receiver of claim 21, wherein:

said curved region detector includes one or more lookup tables for detecting said data from said complex components.

23. The receiver of claim 21, wherein:

said nonlinear decision boundaries are defined according to a scale factor.

24. The receiver of claim 23, wherein:

said nonlinear decision boundaries are defined by rotated versions of $\phi + \alpha\rho^2 = 0$, where ρ is a radius, ϕ is an angle, and α is said scale factor.

25. The receiver of claim 23, wherein:

said scale factor is a function of a number N of said spans.

26. The receiver of claim 23, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

27. The receiver of claim 23, wherein:

said scale factor is approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is the noise variance for one of said spans.

28. The receiver of claim 23, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean phase shift due to Kerr effect.

29. The receiver of claim 21, wherein:

the complex signal estimator includes a phase estimator for estimating a phase of said optical signal; and a signal strength estimator for estimating said signal strength of said optical signal.

30. The receiver of claim 29, wherein:

said phase is a differential phase; and

said signal strength is a differential signal strength.

31. The receiver of claim 21, wherein:

the complex signal estimator includes a quadrature estimator for estimating quadrature components of said optical signal.

32. The receiver of claim 31, wherein:

said quadrature components are differential quadrature components.

33. An optical receiver for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

a frequency estimator for estimating a frequency of said optical signal;

a signal strength estimator for estimating a signal strength of said optical signal; and

an intensity-scaled phase noise compensator using said signal strength for compensating for said phase noise in said frequency and providing a phase noise compensated representation of said optical signal.

34. The receiver of claim 33, wherein:

said phase noise is Kerr effect phase noise.

35. The receiver of claim 33, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

36. The receiver of claim 33, wherein:

said phase noise is induced by additive noise in said spans.

37. The receiver of claim 33, further comprising:

a frequency data detector using said phase noise compensated representation for detecting data carried on said optical signal.

38. The receiver of claim 33, wherein:

the intensity-scaled phase noise compensator uses information for a scale factor for scaling said signal strength, said scaled signal strength used for compensating for said phase noise.

39. The receiver of claim 38, wherein:

said scale factor is a function of a number N of said spans.

40. The receiver of claim 38, wherein:

said scale factor is approximated by one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

41. The receiver of claim 38, wherein:

said scale factor is approximated by

$$\gamma L_{eff} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is the noise variance for one of said spans.

42. The receiver of claim 38, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean phase shift due to Kerr effect.

43. The receiver of claim 38, wherein:

the intensity-scaled phase noise compensator further uses information for a symbol time period for scaling said signal strength for compensating for said phase noise.

44. The receiver of claim 43, wherein:

the intensity-scaled phase noise compensator scales said frequency by said scale factor divided by said symbol time period.

45. The receiver of claim 33, wherein:

said optical signal carries data in a form of frequency modulation; and

said phase noise compensated representation represents said frequency modulation.

46. The receiver of claim 33, wherein:

the intensity-scaled phase noise compensator includes a scaler for scaling said signal strength by a scale factor divided by a symbol time period for providing a scaled signal strength, a frequency shifter for shifting said frequency by said scaled signal strength, and a frequency data detector using said shifted frequency for detecting modulation data carried on said optical signal.

47. An optical phase noise compensator for reducing nonlinear phase noise accumulated over one or more spans in an optical signal, comprising:

an intensity scaler for receiving an optical signal and providing a scaled signal strength; and

an optical phase modulator for modulating said received optical signal with said scaled signal strength for issuing an output optical signal having a reduced level of said phase noise.

48. The compensator of claim 47, wherein:

said phase noise is Kerr effect phase noise.

49. The compensator of claim 47, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

50. The compensator of claim 47, wherein:

said phase noise is induced by additive noise in said spans.

51. The compensator of claim 47, wherein:

the intensity scaler includes a signal strength estimator for estimating a signal strength of said received optical signal and a multiplier for multiplying said signal strength by a scale factor for providing said scaled signal strength.

52. The compensator of claim 51, wherein:

said scale factor is a function of a number N of said spans.

53. The compensator of claim 51, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

54. The compensator of claim 51, wherein:

said scale factor is approximately

$$\gamma L_{\mathrm{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said received optical signal without noise, and said σ^2 is a noise variance for one of said spans.

55. The receiver of claim 51, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said received optical signal, said mean phase shift due to Kerr effect.

56. A method for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

estimating complex components representative of said optical signal; and

using information for a signal strength of said optical signal for compensating for said phase noise in said complex components and providing a phase noise compensated representation of said optical signal.

57. The method of claim 56, wherein:

said phase noise is Kerr effect phase noise.

58. The method of claim 56, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

59. The method of claim 56, wherein:

said phase noise is induced by additive noise in said spans.

60. The method of claim 56, wherein:

the step compensating for said phase noise includes steps of scaling said signal strength in order to provide a scaled signal strength; and using said scaled signal strength for compensating for said phase noise.

61. The method of claim 60, wherein:

said step of scaling said signal strength includes scaling by a function of a number N of said spans.

62. The method of claim 60, wherein:

said step of scaling said signal strength includes scaling by approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for said spans (L_{eff}) times a sum of one plus said N.

63. The method of claim 60, wherein:

said step of scaling said signal strength includes scaling by approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is a noise variance for one of said spans.

64. The method of claim 60, wherein:

said step of scaling said signal strength includes scaling by approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean nonlinear phase shift due to Kerr effect.

65. The method of claim 56, wherein:

said optical signal carries data in a form of phase modulation; and

said phase noise compensated representation represents said phase modulation.

66. The method of claim 56, wherein:

said optical signal carries data in a form of phase and amplitude modulation; and

said phase noise compensated representation represents said phase and amplitude modulation.

67. The method of claim 56, further comprising:

estimating said signal strength of said optical signal; and wherein:

the step of compensating for said phase noise includes steps of scaling said signal strength; and rotating said complex components by said scaled signal strength for providing said phase noise compensated representation of said optical signal.

68. The method of claim 67, wherein:

said step of compensating for said phase noise further includes using said phase noise compensated representation for detecting modulation data carried on said optical signal.

69. The method of claim 67, wherein:

the step of estimating complex components further includes estimating a phase of said optical signal; and

said step of rotating said estimated complex components includes rotating said phase by said scaled signal strength for providing said phase noise compensated phase representation.

70. The method of claim 69, wherein:

said phase is a differential phase; and

said signal strength is a differential signal strength.

71. The method of claim 69, wherein:

said step of rotating said phase includes adding said scaled signal strength to said phase for providing said phase noise compensated phase representation.

72. The method of claim 67, wherein:

the step of estimating complex components further includes estimating quadrature components of said optical signal; and

said step of rotating said complex components includes rotating said quadrature components by said scaled signal strength for providing said phase noise compensated representation of said optical signal.

73. The method of claim 72, wherein:

said step of rotating said quadrature components including rotating according to

$$\hat{x}_c = \hat{x}_R \cos(\alpha\hat{P}_N) - \hat{y}_R \sin(\alpha\hat{P}_N)$$
$$\hat{y}_c = \hat{x}_R \sin(\alpha\hat{P}_N) + \hat{y}_R \cos(\alpha\hat{P}_N)$$

where $\hat{x}_R$ and $\hat{y}_R$ are said quadrature components, $\hat{P}_N$ is said signal strength, α is said scale factor, and $\hat{x}_c$ and $\hat{y}_c$ are said phase noise compensated representation.

74. The method of claim 72, wherein:

said quadrature components are differential quadrature components; and said signal strength is a differential signal strength.

75. The method of claim 74, wherein:

said step of rotating said differential quadrature components includes rotating according to

$$\Delta\hat{x}_c = \Delta\hat{x}_R \cos(\alpha\Delta\hat{P}_N) - \Delta\hat{y}_R \sin(\alpha\Delta\hat{P}_N)$$
$$\Delta\hat{y}_c = \Delta\hat{x}_R \sin(\alpha\hat{P}_N) + \Delta\hat{y}_R \cos(\alpha\Delta\hat{P}_N)$$

where $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ are said differential quadrature components, $\Delta\hat{P}_N$ is said differential signal strength, α is said scale factor, and $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ are said phase noise compensated representation.

76. The method of claim 56, wherein:

the step of compensating for said phase noise includes steps of applying one or more nonlinear decision boundaries for separating complex decision space into curved regions; and detecting data carried on said optical signal based upon which one of said curved regions contains said estimated complex components.

77. The method of claim 76, wherein:

the step of compensating for said phase noise further includes storing information for said curved regions as one or more lookup tables; and using said lookup tables for detecting said data from said complex components.

78. The method of claim 76, wherein:

said nonlinear decision boundaries are curved according to a scale factor.

79. The method of claim 78, wherein:

said nonlinear decision boundaries are defined by rotated versions of $\phi + \alpha\rho^2 = 0$, where ρ is a radius, ϕ is an angle, and α is said scale factor.

80. The method of claim 78, wherein:

said scale factor is a function of a number N of said spans.

81. The method of claim 78, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

82. The method of claim 78, wherein:

said scale factor is approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said $\bar{E}_0$ is a calculated power expected of said optical signal without noise, and said σ^2 is the noise variance for one of said spans.

83. The method of claim 78, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean phase shift due to Kerr effect.

84. The method of claim 76, wherein:

the step of estimating complex components includes steps of estimating a phase of said optical signal; and further comprising a step of estimating said signal strength of said optical signal.

85. The method of claim 84, wherein:

said phase is a differential phase; and

said signal strength is a differential signal strength.

86. The method of claim 76, wherein:

the step of estimating complex components includes a step of estimating quadrature components of said optical signal.

87. The method of claim 86, wherein:

said quadrature components are differential quadrature components.

88. A method for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

estimating a frequency of said optical signal;

estimating a signal strength of said optical signal; and

using said signal strength for compensating for said phase noise in said frequency for providing a phase noise compensated representation of said optical signal.

89. The method of claim 88, wherein:

said phase noise is Kerr effect phase noise.

90. The method of claim 88, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

91. The method of claim 88, wherein:

said phase noise is induced by additive noise in said spans.

92. The method of claim 88, further comprising:

using said phase noise compensated representation for detecting data carried on said optical signal.

93. The method of claim 88, wherein:

the step of compensating for said phase noise includes steps of scaling said signal strength in order to provide a scaled signal strength; and using said scaled signal strength for compensating for said phase noise.

94. The method of claim 93, wherein:

said step of scaling said signal strength includes scaling by a function of a number N of said spans.

95. The method of claim 93, wherein:

said step of scaling said signal strength includes scaling by approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

96. The method of claim 93, wherein:

said step of scaling said signal strength includes scaling by approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is the noise variance for one of said spans.

97. The method of claim 93, wherein:

said step of scaling said signal strength includes scaling by approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean phase shift due to Kerr effect.

98. The method of claim 93, further comprising:

using information for a symbol time period for scaling said signal strength for compensating for said phase noise in said frequency.

99. The method of claim 98, wherein:

said step of using information for a symbol time period for scaling said signal strength further includes dividing by said symbol time period.

100. The method of claim 88, wherein:

said optical signal carries data in a form of frequency modulation; and said phase noise compensated representation represents said frequency modulation.

101. The method of claim 88, wherein:

the step of compensating for said phase noise includes steps of scaling said signal strength by a scale factor divided by a symbol time period for providing a scaled signal strength; shifting said frequency by said scaled signal strength; and using said shifted frequency for detecting modulation data carried on said optical signal.

102. A method for reducing nonlinear phase noise accumulated over one or more spans in an optical signal, comprising:

receiving said optical signal;

determining a scaled signal strength for said received optical signal;

modulating said received optical signal with said scaled signal strength for issuing an output optical signal having a reduced level of said phase noise.

103. The method of claim 102, wherein:

said phase noise is Kerr effect phase noise.

104. The method of claim 102, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

105. The method of claim 102, wherein:

said phase noise is induced by additive noise in said spans.

106. The method of claim 102, wherein:

the step of determining a scaled signal strength includes estimating a signal strength of said received optical signal; and multiplying said signal strength by a scale factor for providing said scaled signal strength.

107. The method of claim 106, wherein:

said scale factor is a function of a number N of said spans.

108. The method of claim 106, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

109. The method of claim 106, wherein:

said scale factor is approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said received optical signal without noise, and said σ^2 is a noise variance for one of said spans.

110. The method of claim 106, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said received optical signal, said mean phase shift due to Kerr effect.

111. An optical receiver for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

a complex signal estimator for estimating differential complex components representative of said optical signal; and

an intensity-scaled phase noise compensator using information for a differential signal strength of said optical signal for compensating for said phase noise in said differential complex components and providing a phase noise compensated representation of said optical signal.

112. The receiver of claim 111, wherein:

said phase noise is Kerr effect phase noise.

113. The receiver of claim 111, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

114. The receiver of claim 111, wherein:

said phase noise is induced by additive noise in said spans.

115. The receiver of claim 111, wherein:

the phase noise compensator uses information for a scale factor for scaling said differential signal strength in order to provide a scaled differential signal strength, said scaled differential signal strength used for compensating for said phase noise.

116. The receiver of claim 115, wherein:

said scale factor is a function of a number N of said spans.

117. The receiver of claim 115, wherein:

said scale factor is approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for one of said spans (L_{eff}) times a sum of one plus said N.

118. The receiver of claim 115, wherein:

said scale factor is approximately

$$\gamma L_{eff} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is a noise variance for one of said spans.

119. The receiver of claim 115, wherein:

said scale factor is approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean nonlinear phase shift due to Kerr effect..

120. The receiver of claim 111, wherein:

said optical signal carries data in a form of differential phase modulation; and

said phase noise compensated representation represents said differential phase modulation.

121. The receiver of claim 111, wherein:

said optical signal carries data in a form of differential phase and amplitude modulation; and

said phase noise compensated representation represents said differential phase and amplitude modulation.

122. The receiver of claim 111, wherein:

the receiver includes a signal strength estimator for estimating said differential signal strength of said optical signal; and

the phase noise compensator includes a scaler storing information for a scale factor and using said scale factor for scaling said differential signal strength, and a rotator for rotating said differential complex components by said scaled differential signal strength for providing said phase noise compensated representation of said optical signal.

123. The receiver of claim 122, wherein:

the phase noise compensator further includes a data detector using said phase noise compensated representation for detecting modulation data carried on said optical signal.

124. The receiver of claim 122, wherein:

the complex signal estimator further includes a phase estimator for estimating a differential phase; and

said rotator rotates said differential phase by said scaled differential signal strength for providing said phase noise compensated representation.

125. The receiver of claim 124, wherein:

said rotator rotates said differential phase by adding said scaled differential signal strength to said differential phase for providing said phase noise compensated phase representation.

126. The receiver of claim 122, wherein:

the complex signal estimator further includes a quadrature estimator for estimating differential quadrature components; and

said rotator rotates said differential quadrature components by said scaled differential signal strength for providing said phase noise compensated representation.

127. The receiver of claim 126, wherein:

said rotator rotates said differential quadrature components according to

$$\Delta\hat{x}_c = \Delta\hat{x}_R \cos(\alpha\Delta\hat{P}_N) - \Delta\hat{y}_R \sin(\alpha\Delta\hat{P}_N)$$
$$\Delta\hat{y}_c = \Delta\hat{x}_R \sin(\alpha\hat{P}_N) + \Delta\hat{y}_R \cos(\alpha\Delta\hat{P}_N)$$

where $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ are said differential quadrature components, $\Delta\hat{P}_N$ is said differential signal strength, α is said scale factor, and $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ are said phase noise compensated representation.

128. A method for receiving an optical signal having nonlinear phase noise accumulated over one or more spans, comprising:

estimating differential complex components representative of said optical signal; and

using information for a differential signal strength for compensating for said phase noise in said differential complex components for providing a phase noise compensated representation of said optical signal.

129. The method of claim 128, wherein:

said phase noise is Kerr effect phase noise.

130. The method of claim 128, wherein:

said phase noise is induced by fiber nonlinearity in said spans.

131. The method of claim 128, wherein:

said phase noise is induced by additive noise in said spans.

132. The method of claim 128, wherein:

the step compensating for said phase noise includes steps of scaling said differential signal strength in order to provide a scaled differential signal strength; and using said scaled differential signal strength for compensating for said phase noise.

133. The method of claim 132, wherein:

said step of scaling said differential signal strength includes scaling by a function of a number N of said spans.

134. The method of claim 132, wherein:

said step of scaling said differential signal strength includes scaling by approximately one half a nonlinear coefficient of an optical fiber (γ) times an effective nonlinear length for said spans (L_{eff}) times a sum of one plus said N.

135. The method of claim 132, wherein:

said step of scaling said differential signal strength includes scaling by approximately

$$\gamma L_{\text{eff}} \frac{N+1}{2} \cdot \frac{|E_0|^2 + (2N+1)\sigma^2/3}{|E_0|^2 + N\sigma^2}$$

where said N is the number of said spans, said γ is a nonlinear coefficient of an optical fiber, said L_{eff} is an effective nonlinear length for one of said spans, said E_0 is a calculated power expected of said optical signal without noise, and said σ^2 is a noise variance for one of said spans.

136. The method of claim 132, wherein:

said step of scaling said differential signal strength includes scaling by approximately one-half the ratio of a mean nonlinear phase shift and a mean signal power of said optical signal, said mean nonlinear phase shift due to Kerr effect..

137. The method of claim 128, wherein:

said optical signal carries data in a form of differential phase modulation; and

said phase noise compensated representation represents said differential phase modulation.

138. The method of claim 128, wherein:

said optical signal carries data in a form of differential phase and amplitude modulation; and

said phase noise compensated representation represents said differential phase and amplitude modulation.

139. The method of claim 128, further comprising:

estimating said differential signal strength of said optical signal; and wherein:

the step of compensating for said phase noise includes steps of scaling said differential signal strength; and rotating said differential complex components by said scaled differential signal strength for providing said phase noise compensated representation of said optical signal.

140. The method of claim 139, wherein:

said step of compensating for said phase noise further includes using said phase noise compensated representation for detecting modulation data carried on said optical signal.

141. The method of claim 139, wherein:

the step of estimating differential complex components further includes estimating a differential phase of said optical signal; and

said step of rotating said differential complex components includes rotating said differential phase by said scaled differential signal strength for providing said phase noise compensated phase representation.

142. The method of claim 141, wherein:

the step rotating said differential phase includes adding said scaled differential signal strength to said differential phase for providing said phase noise compensated phase representation.

143. The method of claim 139, wherein:

the step of estimating differential complex components further includes estimating differential quadrature components of said optical signal; and

said step of rotating said differential complex components includes rotating said differential quadrature components by said scaled differential signal strength for providing said phase noise compensated representation of said optical signal.

144. The method of claim 143, wherein:

said step of rotating said differential quadrature components including rotating according to

$$\Delta\hat{x}_c = \Delta\hat{x}_R \cos(\alpha\Delta\hat{P}_N) - \Delta\hat{y}_R \sin(\alpha\Delta\hat{P}_N)$$
$$\Delta\hat{y}_c = \Delta\hat{x}_R \sin(\alpha\hat{P}_N) + \Delta\hat{y}_R \cos(\alpha\Delta\hat{P}_N)$$

where $\Delta\hat{x}_R$ and $\Delta\hat{y}_R$ are said differential quadrature components, $\Delta\hat{P}_N$ is said differential signal strength, α is said scale factor, and $\Delta\hat{x}_c$ and $\Delta\hat{y}_c$ are said phase noise compensated representation.

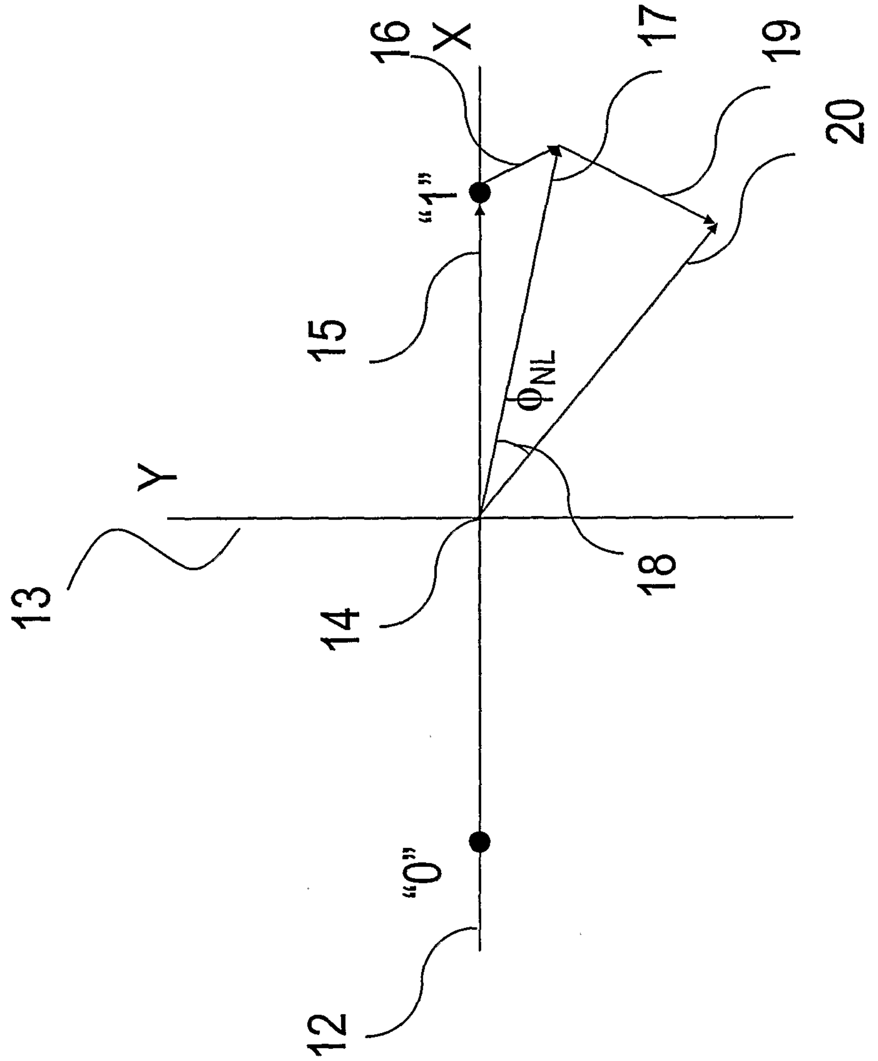


Fig. 1
PRIOR ART

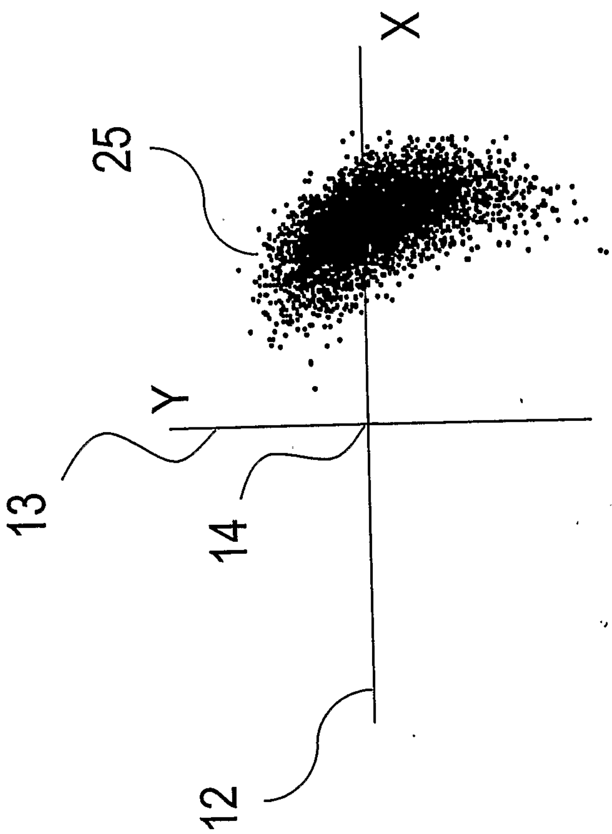


Fig. 2
PRIOR ART

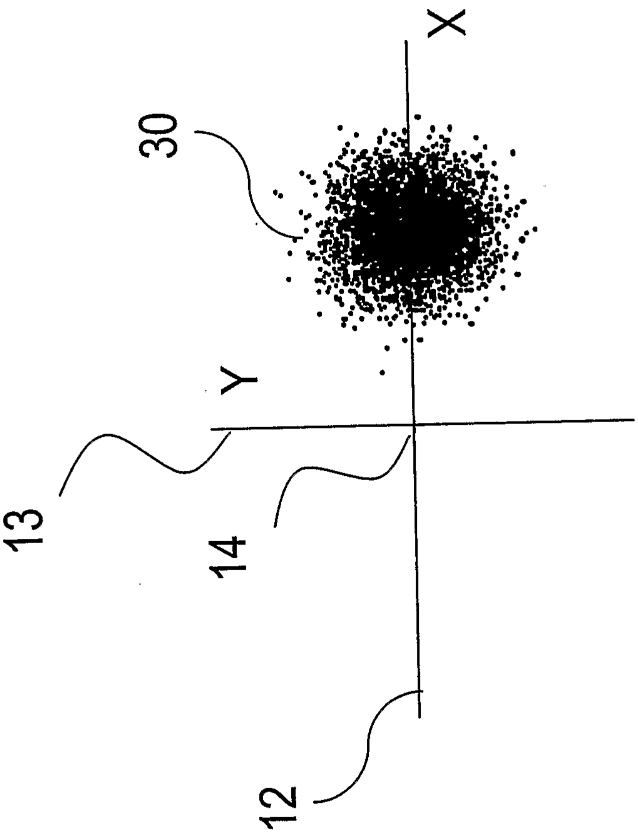


Fig. 3

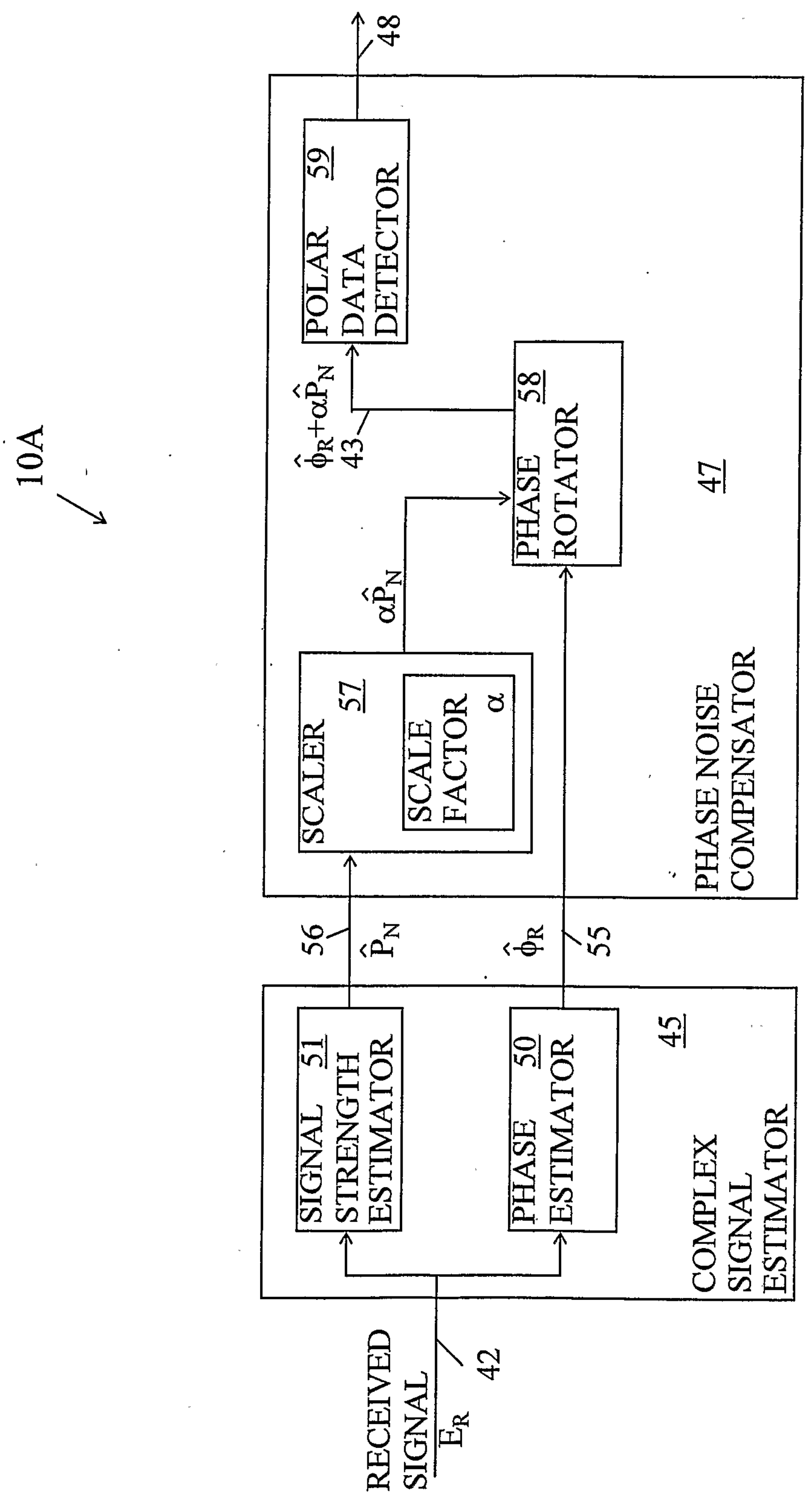

10A
RECEIVED SIGNAL E_R
42
SIGNAL STRENGTH ESTIMATOR 51
PHASE ESTIMATOR 50
COMPLEX SIGNAL ESTIMATOR 45
56
$\hat{P}_N$
$\hat{\phi}_R$
55
SCALER 57
SCALE FACTOR α
$\alpha\hat{P}_N$
PHASE ROTATOR 58
$\hat{\phi}_R+\alpha\hat{P}_N$
43
POLAR DATA DETECTOR 59
48
47
PHASE NOISE COMPENSATOR

Fig. 4

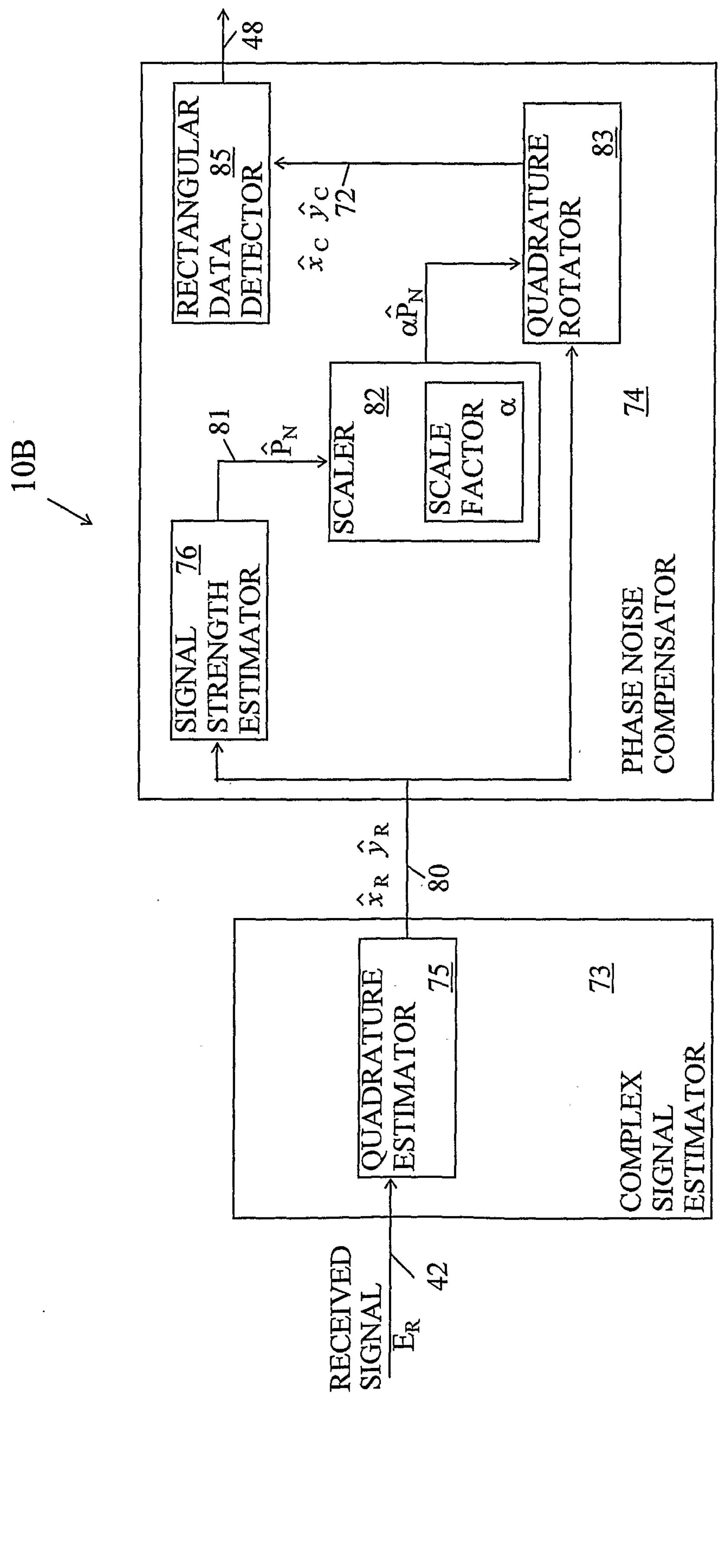

10B
RECEIVED SIGNAL
$\underline{E}_R$
42
QUADRATURE ESTIMATOR 75
COMPLEX SIGNAL ESTIMATOR
73
$\hat{x}_R\ \hat{y}_R$
80
SIGNAL STRENGTH ESTIMATOR 76
81
$\hat{P}_N$
SCALER 82
SCALE FACTOR α
$\alpha\hat{P}_N$
QUADRATURE ROTATOR 83
$\hat{x}_C\ \hat{y}_C$
72
RECTANGULAR DATA DETECTOR 85
48
PHASE NOISE COMPENSATOR
74

Fig. 5

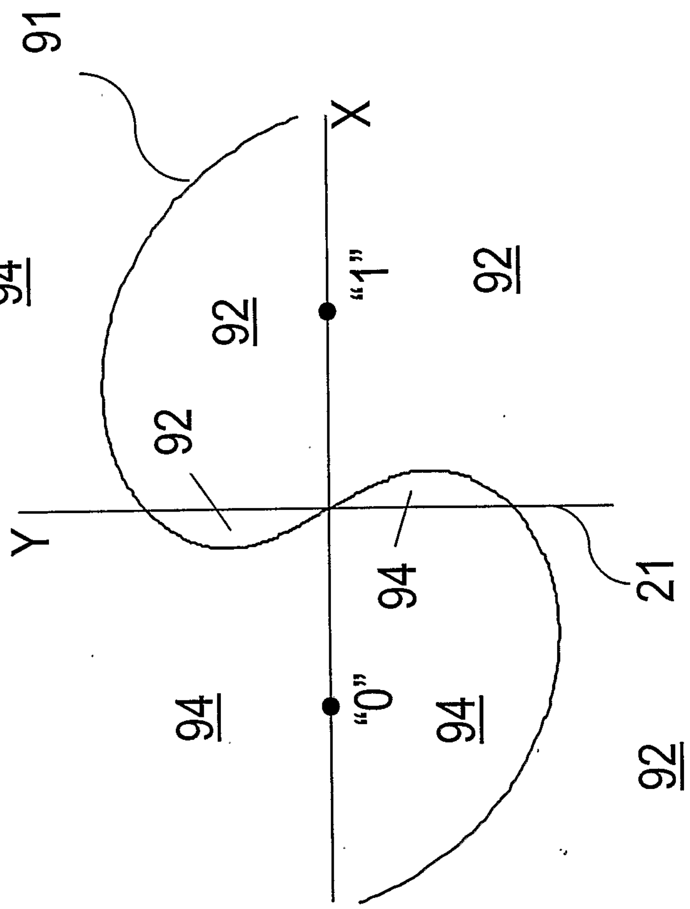
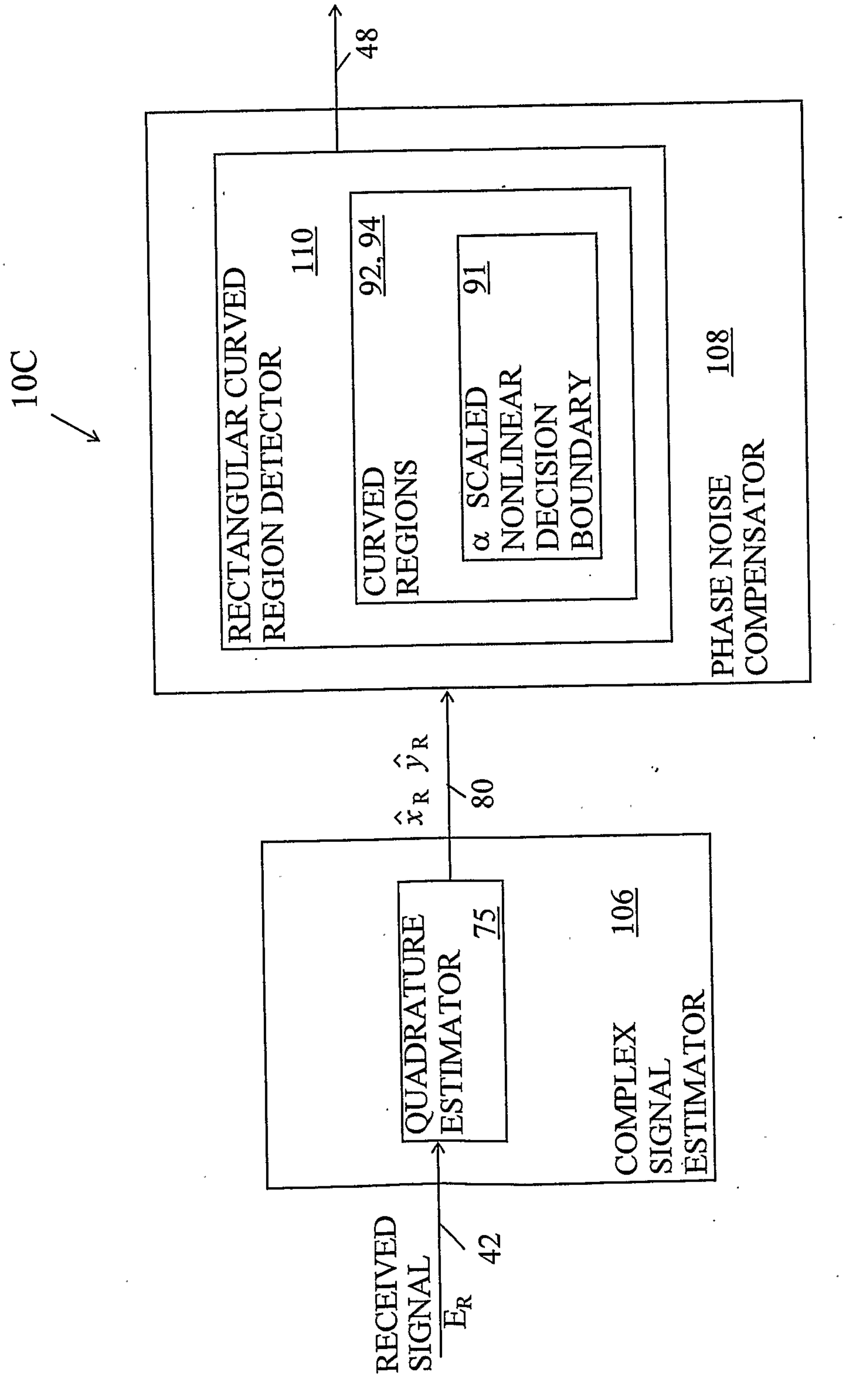


Fig. 6


10C
RECTANGULAR CURVED REGION DETECTOR 110
CURVED REGIONS 92, 94
α SCALED NONLINEAR DECISION BOUNDARY 91
PHASE NOISE COMPENSATOR 108
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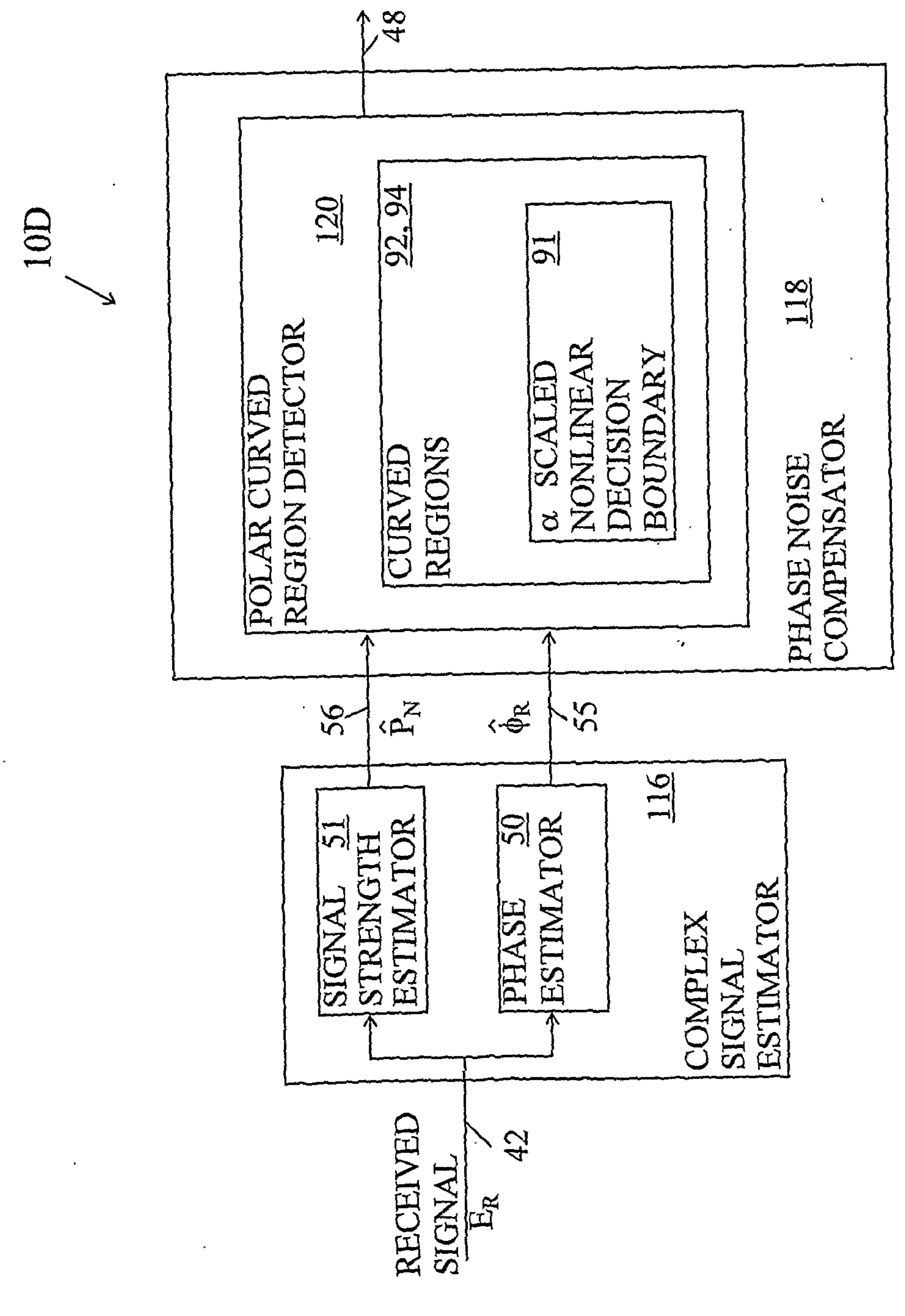
$\hat{x}_R$ $\hat{y}_R$
80
QUADRATURE ESTIMATOR 75
COMPLEX SIGNAL ESTIMATOR 106
RECEIVED SIGNAL E_R
42

Fig. 7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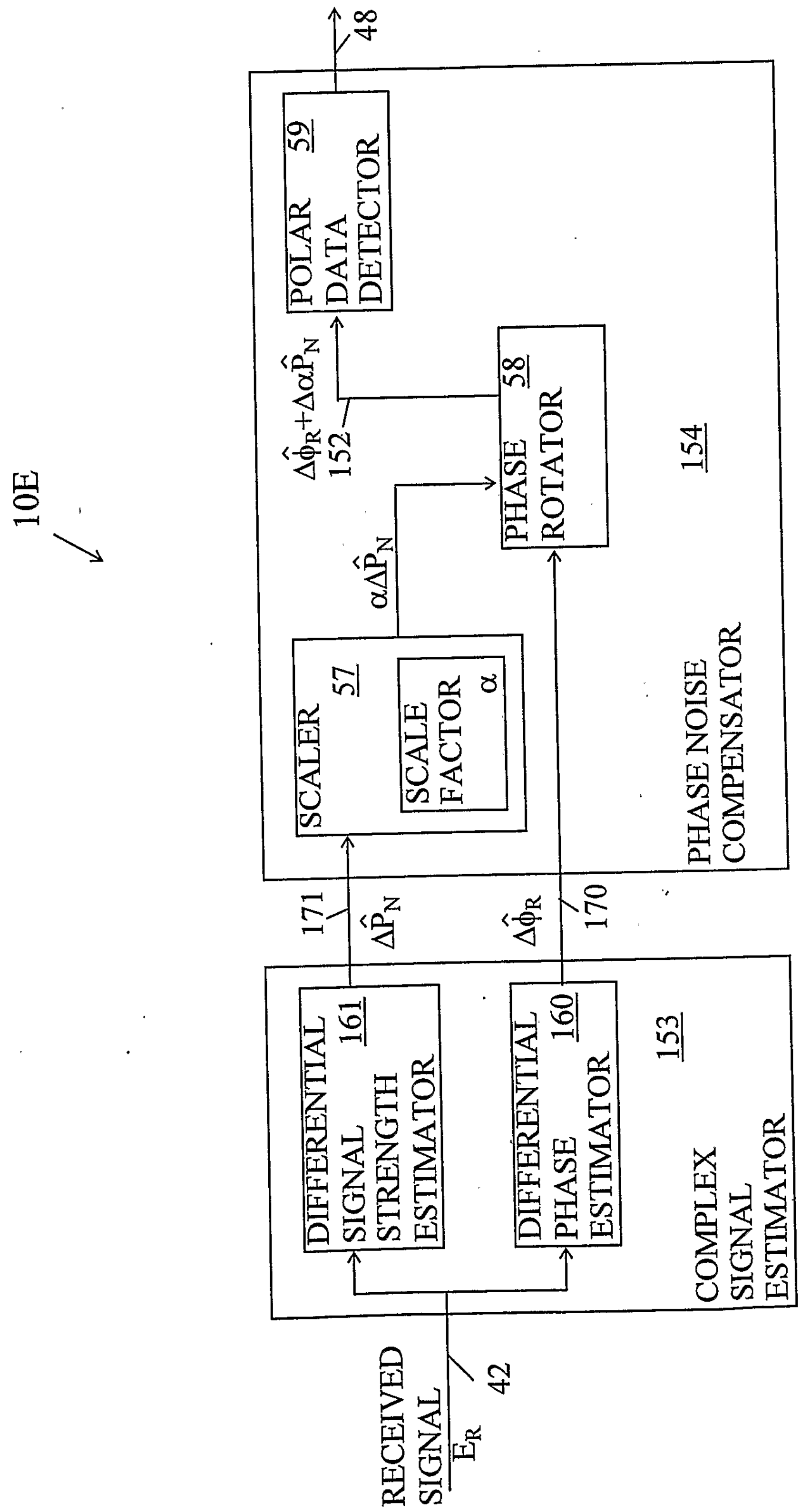
POLAR CURVED REGION DETECTOR 120
CURVED REGIONS 92, 94
α SCALED NONLINEAR DECISION BOUNDARY 91
PHASE NOISE COMPENSATOR 118
48
56
$\hat{P}_N$
$\hat{\phi}_R$
55
SIGNAL STRENGTH ESTIMATOR 51
PHASE ESTIMATOR 50
COMPLEX SIGNAL ESTIMATOR 116
RECEIVED SIGNAL
E_R
42

Fig. 8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RECEIVED SIGNAL E_R
42
DIFFERENTIAL SIGNAL STRENGTH ESTIMATOR 161
DIFFERENTIAL PHASE ESTIMATOR 160
153
COMPLEX SIGNAL ESTIMATOR
171
$\Delta\hat{P}_N$
$\Delta\hat{\phi}_R$
170
SCALER 57
SCALE FACTOR α
$\alpha\Delta\hat{P}_N$
PHASE ROTATOR 58
$\Delta\hat{\phi}_R+\Delta\alpha\hat{P}_N$
152
POLAR DATA DETECTOR 59
48
154
PHASE NOISE COMPENSATOR

Fig. 9

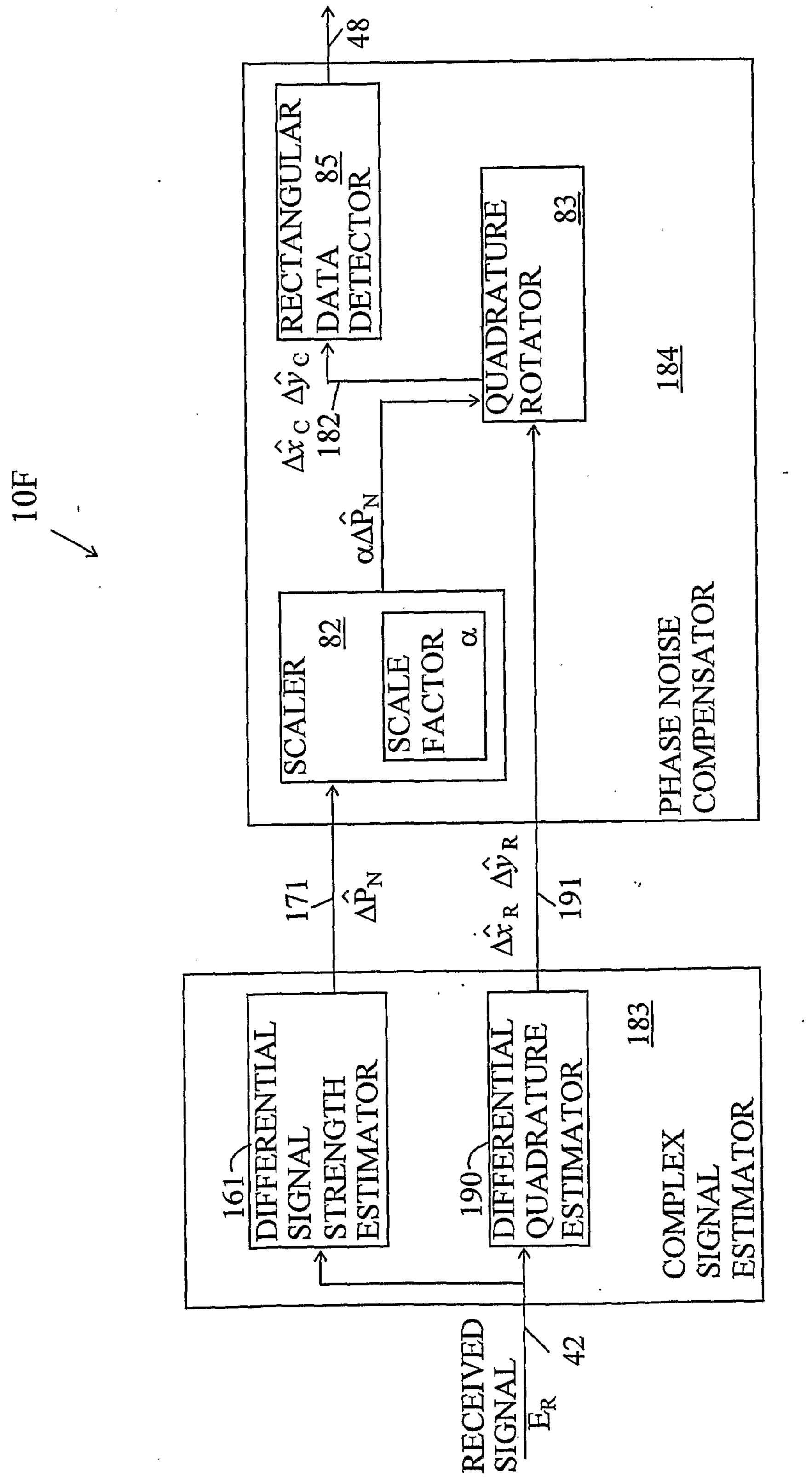

10F
RECEIVED SIGNAL $\underline{E}_R$
42
COMPLEX SIGNAL ESTIMATOR
183
161
DIFFERENTIAL SIGNAL STRENGTH ESTIMATOR
190
DIFFERENTIAL QUADRATURE ESTIMATOR
171
$\Delta\hat{P}_N$
$\Delta\hat{x}_R$ $\Delta\hat{y}_R$
191
PHASE NOISE COMPENSATOR
184
SCALER
82
SCALE FACTOR
α
$\alpha\Delta\hat{P}_N$
QUADRATURE ROTATOR
83
$\Delta\hat{x}_C$ $\Delta\hat{y}_C$
182
RECTANGULAR DATA DETECTOR
85
48

Fig. 10

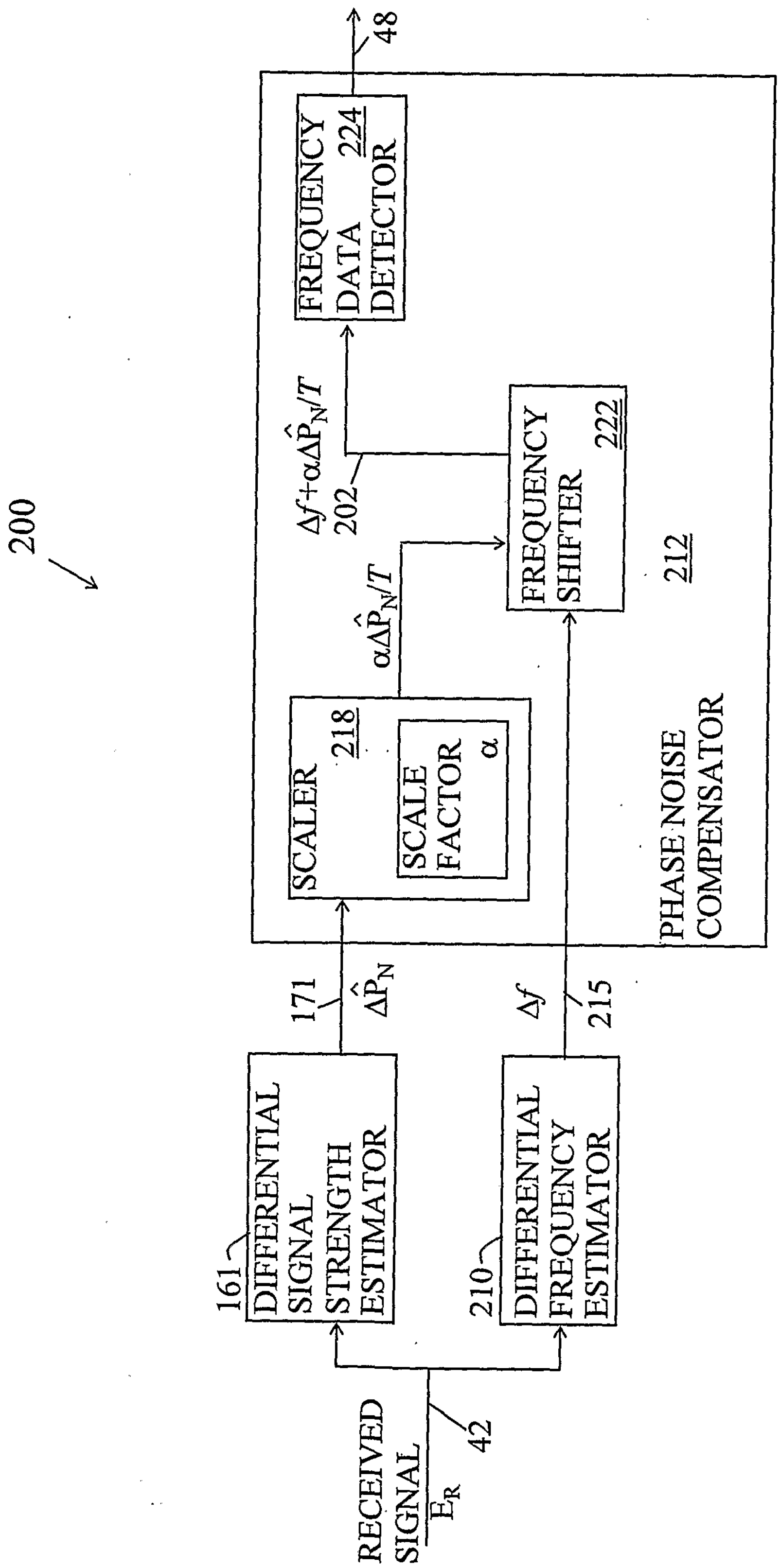
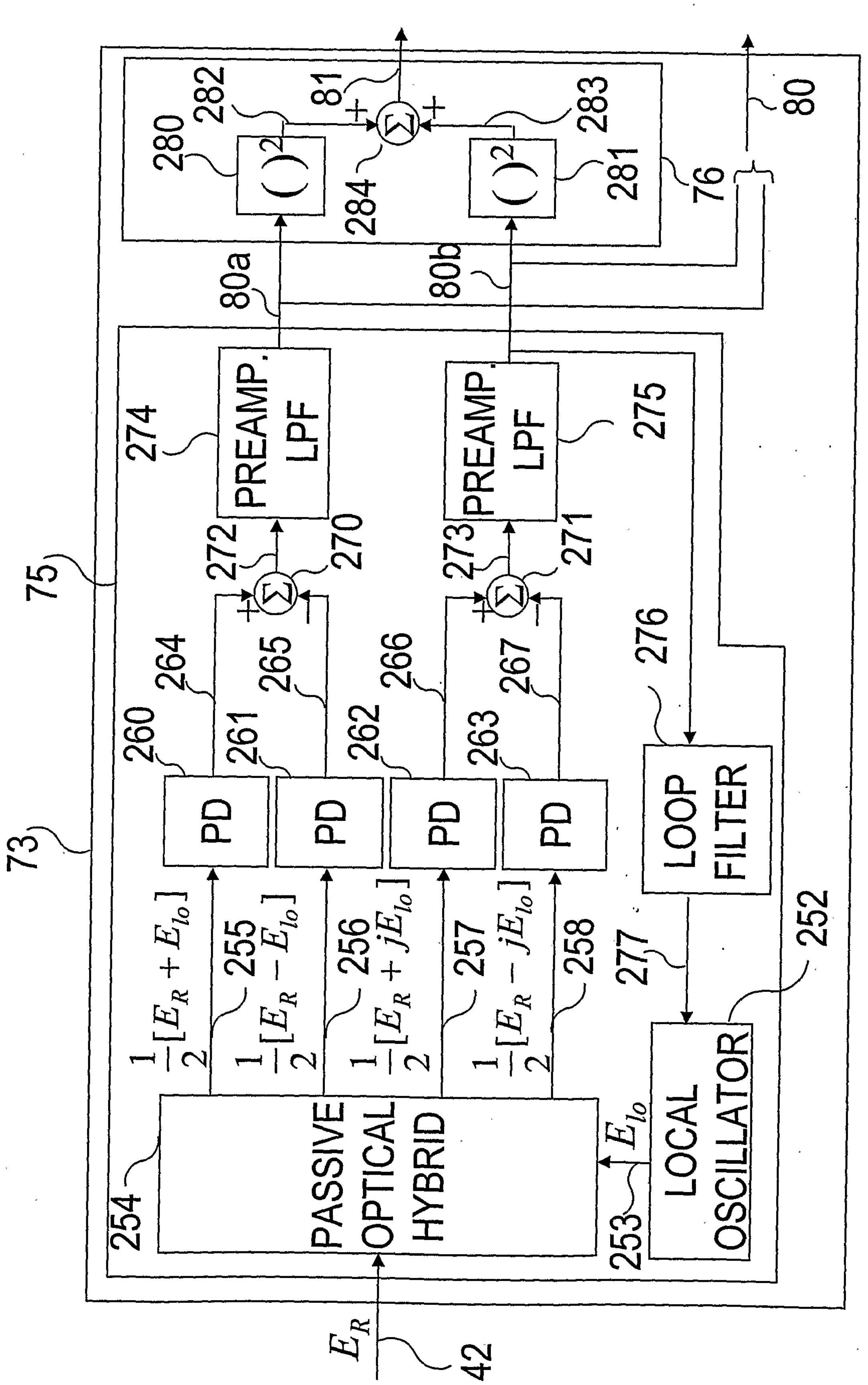

200
RECEIVED SIGNAL E_R
42
161
DIFFERENTIAL SIGNAL STRENGTH ESTIMATOR
210
DIFFERENTIAL FREQUENCY ESTIMATOR
171
$\Delta\hat{P}_N$
Δf
215
SCALER 218
SCALE FACTOR α
$\alpha\Delta\hat{P}_N/T$
FREQUENCY SHIFTER 222
202
$\Delta f+\alpha\Delta\hat{P}_N/T$
FREQUENCY DATA DETECTOR 224
48
212
PHASE NOISE COMPENSATOR

Fig. 11



PASSIVE OPTICAL HYBRID
LOCAL OSCILLATOR
LOOP FILTER
PD
PD
PD
PD
PREAMP. LPF
PREAMP. LPF
$\frac{1}{2}[E_R + E_{lo}]$
$\frac{1}{2}[E_R - E_{lo}]$
$\frac{1}{2}[E_R + jE_{lo}]$
$\frac{1}{2}[E_R - jE_{lo}]$
E_{lo}
E_R
$( )^2$
$( )^2$
Σ
42
73
75
76
80
80a
80b
81
252
253
254
255
256
257
258
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284

Fig. 12

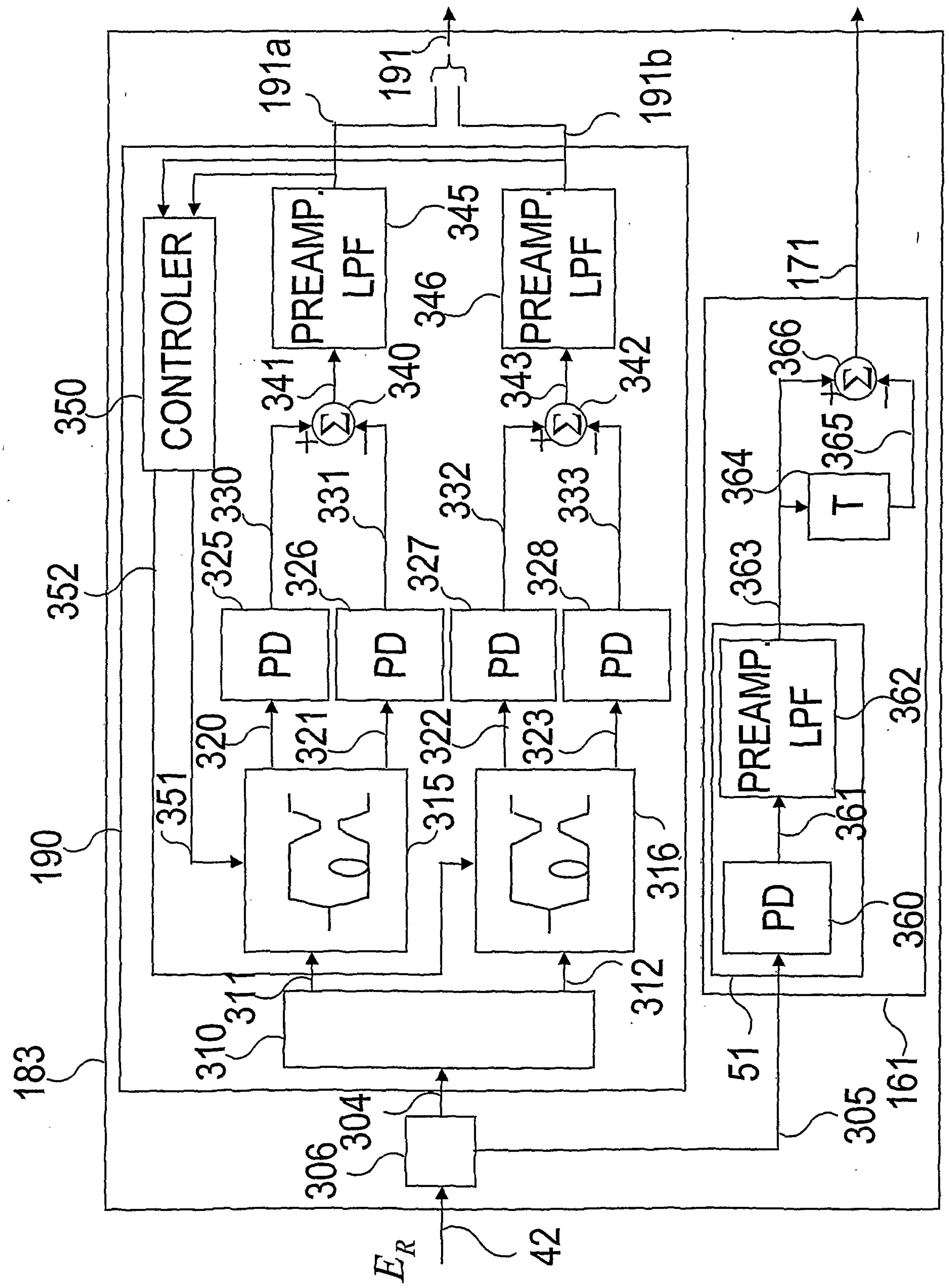
CONTROLER
PREAMP. LPF
PREAMP. LPF
PREAMP. LPF
PD
PD
PD
PD
PD
T
E_R
42
183
190
191
191a
191b
171
161
51
304
305
306
310
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Fig. 13

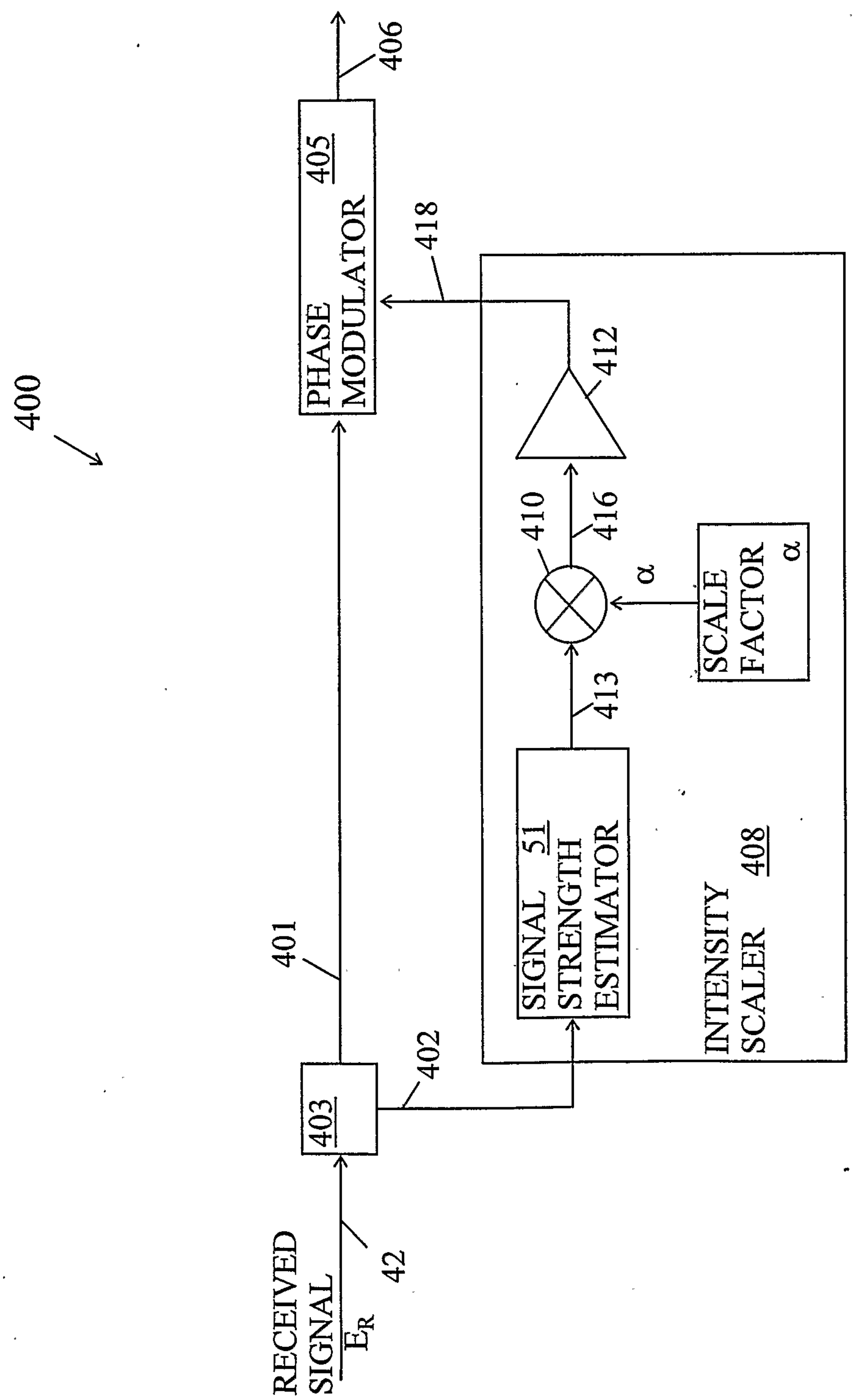
400
RECEIVED SIGNAL
E_R
42
403
402
401
PHASE MODULATOR 405
406
418
412
410
416
α
SCALE FACTOR α
413
SIGNAL 51 STRENGTH ESTIMATOR
INTENSITY SCALER 408

Fig. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US03/18867

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04B 10/06, 1/10; H03D 1/06
US CL : 398/208; 375/346

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)
U.S. : 398/148, 173-181, 208, 212-214; 375/226, 346-351, 371-376; 250/201.9; 455/114.3; 330/149

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
IEEE Xplore, Optics InfoBase

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, P --- Y, P	HO, K. and J.M. KAHN. "Electronic compensation technique to mitigate nonlinear phase noise." arXiv.org e-Print archive. 29 May 2003: 1-5. http://arxiv.org/abs/physics/0211097.	1-10, 21-30, 56-65, 76-85, 111-120, 128-137 ----------- 11-20, 31-55, 66-75, 86-110, 121-127, 138-144
Y	GORDON, J.P. and L.F. MOLLENAUER. "Phase noise in photonic communications systems using linear amplifiers." 01 December 1990, Vol. 15, No. 23: 1351-1353 -- see whole document --	1-6, 10-25, 29-39, 43-52, 56-61, 65-80, 84-94, 98-107, 111-116, 120-134, 137-144
Y, P	US 6,445,752 B1 (JIANG et al.) 03 September 2002 (03.09.2002) abstract; Figs. 2-5; cols. 3-5; col. 6, lines 4, 21-25, 63-67; col. 7, lines 1-5.	1-144

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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
12 November 2003 (12.11.2003)

Date of mailing of the international search report
11 DEC 2003

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Authorized officer
Jason Chan
Telephone No. 703-305-4750

Eugenia Logan

INTERNATIONAL SEARCH REPORT

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 6,246,717 B1 (CHEN et al.) 12 June 2001 (12.06.2001) abstract; Fig. 4-9; col. 1, lines 6-9, 15-18, 58-60; col. 2, lines 3-5, 46-55; col. 3, lines 45-50, 60-63; col. 7, lines 4-50; col. 10, lines 22-46; col. 11, lines 27-41; cols. 12-13; col. 14, lines 11-22; col. 15, lines 8-36.	1-144
Y	US 4,771,438 A (NASH) 13 September 1988 (13.09.1988) col. 1, lines 23-32.	15, 19-20, 30, 32, 70, 74-75, 85, 87, 111, 115, 120-122, 124-128, 132, 137-139, 141-144
Y	US 5,533,071 A (KRISHNAMURTHY et al.) 02 July 1996 (02.07.1996) abstract; Figs. 2-7; col. 1, lines 25-60; col. 2, line 65 - col. 3, line 38; col. 4, line 1 - col. 5, line 58; col. 6, line 17-25.	1, 5, 12-14, 16-18, 20, 22, 29, 31, 33, 38, 43-44, 46, 56, 60, 67-69, 71-73, 75, 77, 84, 86, 88, 93, 98-99, 101, 111, 115, 122-128, 132, 139-144
Y	US 4,847,477 A (SMITH) 11 July 1989 (11.07.1989) abstract; Figs. 1-2; col. 1, lines 10-11, 23, 42; col. 2, lines 8-27; col. 3, lines 4-40, 53-55; col. 4, lines 7-9.	47, 51, 102, 107
A	US 4,381,546 A (ARMSTRONG) 26 April 1983 (26.04.1983) abstract; Figures; col. 1, lines 23-34, 52-55; col. 2, lines 17-21, 35-46; col. 4, lines 14-16; col. 5, lines 16-18, 45-58.	1, 10-11, 33, 47, 56, 65-66, 88, 102, 111, 128

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US03/18867

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claim Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
Please See Continuation Sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

Continuation of Item 4 of the first sheet:
Typographical error.

NEW TITLE:
OPTICAL RECEIVER HAVING COMPENSATION FOR KERR EFFECT PHASE NOISE

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING
This application contains claims directed to more than one species of the generic invention. These species are deemed to lack unity of invention because they are not so linked as to form a single general inventive concept under PCT Rule 13.1.

In order for more than one species to be examined, the appropriate additional examination fees must be paid. The species are as follows:

Species I)	Fig. 4
Species II)	Fig. 5
Species III)	Fig. 7
Species IV)	Fig. 8
Species V)	Fig. 9
Species VI)	Fig. 10
Species VII)	Fig. 11
Species VIII)	Fig. 14.

The claims are deemed to correspond to the species listed above in the following manner:

Species I)	Claims 1-16 and	56-71
Species II)	Claims 1-13, 17-20 and	56-68, 72-75
Species III)	Claims 1, 21-28, 31-32 and	56, 76-83, 86-87
Species IV)	Claims 1, 21-30 and	56, 76-85
Species V)	Claims 111-125 and	128-142
Species VI)	Claims 111-123, 126-127 and	128-140, 143-144
Species VII)	Claims 33-46 and	88-101
Species VIII)	Claims 47-55 and	102-110.

The following claim(s) are generic: none.
The species listed above do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, the species lack the same or corresponding special technical features for the following reasons:

Each of the species have "special technical features" that other species lack. Additionally, these "special technical features" are not equivalent. Moreover, in some cases, the "special technical features" of one species is mutually exclusive to the "special technical features" of another species.

Regarding Species I-VI:
These species all share the "special technical features" of a complex signal estimator and an intensity-scaled phase noise compensator. However, these features are disclosed by Jiang et al. (U.S. Patent No. 6,445,752 B1). These features are also disclosed by Chen et al. (U.S Patent No. 6,246,717 B1). Accordingly, the "special technical feature" linking these species do not provide a contribution over the prior art, and no single general inventive concept exists. In view of Jiang et al. (or Chen et al.) and the additional distinctions detailed below, there is a lack of unity between these species.

Regarding Species I:
In comparison with Species II, Species I uses a phase estimator instead of a quadrature estimator.
In comparison with Species III and IV, Species I lacks the curved region detectors and lookup tables.
In comparison with Species V and VI, Species I lacks the differential means and components.
In comparison with Species VII, Species I lacks the frequency means.
In comparison with Species VIII, Species I lacks the phase modulator and the output optical signal.

INTERNATIONAL SEARCH REPORT

PCT/US03/18867

Regarding Species II:
In comparison with Species I, Species II uses a quadrature estimator instead of a phase estimator.
In comparison with Species III and IV, Species II lacks the curved region detectors and lookup tables.
In comparison with Species V and VI, Species II lacks the differential means and components.
In comparison with Species VII, Species II lacks the frequency means.
In comparison with Species VIII, Species II lacks the phase modulator and the output optical signal.

Regarding Species III:
In comparison with Species I-II and V-VIII, Species III uses curved region detectors and lookup tables that Species I-II and V-VIII all lack.
In comparison with Species IV, Species III uses a phase estimator instead of a quadrature estimator.

Regarding Species IV:
In comparison with Species I-II and V-VIII, Species IV uses curved region detectors and lookup tables that Species I-II and V-VIII all lack.
In comparison with Species III, Species IV uses a quadrature estimator instead of a phase estimator.

Regarding Species V:
In comparison with Species I-IV and VII-VIII, Species V uses differential means that Species I-IV and VII-VIII all lack.
In comparison with Species VI, Species V uses a differential phase estimator instead of a differential quadrature estimator.

Regarding Species VI:
In comparison with Species I-IV and VII-VIII, Species VI uses differential means that Species I-IV and VII-VIII all lack.
In comparison with Species V, Species VI uses a differential quadrature estimator instead of a differential phase estimator.

Regarding Species VII:
In comparison with all the other species, Species VII uses frequency means that all the other species lack.

Regarding Species VIII:
In comparison with all the other species, Species VIII uses a phase modulator and an output optical signal that all the other species lack.

Should applicant traverse on the ground that the species are not patentably distinct, applicant should submit evidence or identify such evidence now of record showing the species to be obvious variants or clearly admit on the record that this is the case. In either instance, if the International Preliminary Examining Authority (IPEA) finds one of the inventions lacking novelty or lacking an inventive step over the prior art, the evidence or admission may be used to show that the other invention lacks an inventive step under PCT Article 33(3).

In the absence of any response from the applicant, this Authority will establish the International Preliminary Examination Report based on the main invention. The claims drawn to the main invention are as follows:

Claims: 1-16 and 56-71.