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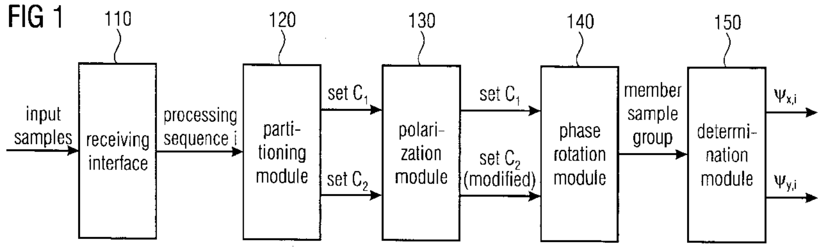



FIG 1

**(57) Abstract**: An apparatus for determining a first and a second phase noise estimate is provided. The apparatus comprises a receiving interface (110), a partitioning module (120), a polarization decision module (130), a phase rotation module (140) and a determination module (150). The receiving interface (110) is configured to receive a plurality of input samples. Moreover, the receiving interface (110) is configured to assign at least some input samples of the plurality of input samples to an input sequence. The partitioning module (120) is configured to classify the input samples of the input sequence into two or more sets. The polarization decision module (130) is configured to decide for some of the input samples, whether to modify either the first amplitude value of the first polarization- component sample or the second amplitude value of the second polarization-component sample. The phase rotation module (140) is configured to determine a member sample group comprising a plurality of member samples, by applying a phase rotation to the first polarization-component sample and the second polarization component sample of some of the input samples. The determination module (150) is configured to determine the first phase noise estimate based on the first polarization-component sample of each member sample of the member sample group and the second phase noise estimate based on the second polarization-component sample of each member sample of the member sample group.

# PHASE NOISE ESTIMATION FOR 6-ARY POLARIZATION-SHIFT KEYING QUADRATURE PHASE-SHIFT KEYING

## Description

The present invention relates to an apparatus and method for determining phase noise estimates, and, in particular, to carrier phase estimation for 6-ary polarization-shift keying quadrature phase-shift keying (6PolSK-QPSK) signals.

Optical communication systems become more and more important. In coherent optical communication systems, phase noise associated with transmitter and local oscillator laser is considered as a main source of sensitivity degradation in systems based on phase-shift keying (PSK). Therefore, estimation of the laser phase noise is one of the essential functions of the digital signal processing in a coherent receiver.

Fig. 7 (a) illustrates a constellation diagram of a 6PolSK-QPSK signal. Dots encircled by dashed lines (red color) correspond to a set $C_1$. Dots encircled by dotted lines (blue color) correspond to a set $C_2$. Fig. 7 (b) illustrates the corresponding time-resolved states of polarization (SOP) on the Poincaré sphere.

The 6PolSK-QPSK format transmits a QPSK symbol in six different states of polarization (see [1], [2], [3]). The 6PolSK-QPSK constellation points may be expressed as $\{\pm\sqrt{2}, \pm\sqrt{2}, 0, 0\}$ with arbitrary sign and permutation as described in [2]. These 24 4D vectors can be described as a combination of two sets, e.g. $C_1$ and $C_2$:

The set $C_1$ includes the following 16 constellation points:

$$\{(\pm\sqrt{2}, 0, \pm\sqrt{2}, 0), (\pm\sqrt{2}, 0, 0, \pm\sqrt{2}), (0, \pm\sqrt{2}, \pm\sqrt{2}, 0), (0, \pm\sqrt{2}, 0, \pm\sqrt{2})\}.$$

Fig. 7 (a) shows the constellation diagram of a 6PolSK-QPSK signal. Constellation points of the set $C_1$ (red color) are encircled by dashed lines. The resulting SOPs of these constellation points are ±45° linear polarization, left-hand circular polarization and right-hand circular polarization. In Stokes space, these SOPs correspond to a Stokes vector $S = \pm S_2$ and $S = \pm S_3$, respectively. A Poincaré-sphere representation of the SOP in Stokes space is shown in Fig. 7 (b).

The set $C_2$ includes the following 8 constellation points:

$$\{(\pm\sqrt{2}, \pm\sqrt{2}, 0, 0), (0, 0, \pm\sqrt{2}, \pm\sqrt{2})\}.$$

In Fig. 7(a), the constellation points of set $C_2$ (blue color) are encircled by dotted lines. The resulting SOP of these constellation points is linear horizontal polarization and linear vertical polarization, corresponding to $S = \pm S_1$ in Stokes space.

Illustrating the above with respect to a particular exemplifying application, Fig. 8 illustrates a constellation diagram of one polarization tributary of a received 126-Gb/s 6PolSK-QPSK signal at 30 dB optical signal-to-noise ratio (OSNR) with a laser linewidth of ~ 100kHz. Fig. 8 (a) illustrates the scenario before carrier phase estimation (CPE); Fig. 8 (b) illustrates the scenario after CPE.

In an optical coherent receiver, the phase noise of the local oscillator laser leads to uncertainty about the phase of the received signal. As an example, Fig. 8(a) shows the constellation diagram of a 126-Gb/s 6PolSK-QPSK signal at 30 dB optical signal-to-noise ratio, where the transmitter and local oscillator lasers have 100kHz linewidth and no carrier phase recovery is applied. After proper carrier phase recovery, the correct signal states are restored (see Fig. 8(b)).

A common algorithm for carrier phase estimation (CPE) in digital coherent receivers is the Viterbi-Viterbi algorithm (see [4]). This algorithm is widely used in coherent receivers for 100G polarization-division multiplexed quadrature phase-shift keying signals (PDM-QPSK). However, it cannot be applied in a straightforward manner to advanced optimized four-dimensional (4D) modulation formats such as 6PolSK-QPSK.

Another CPE algorithm, which is based on using several test phase angles is described in [5]. In principle, the CPE algorithm of [5] is suitable for 6PolSK-QPSK signals. However, compared to a Viterbi-Viterbi CPE, it requires approximately 16 to 64 times the hardware effort. Therefore, it would be highly appreciated, if a hardware-efficient CPE algorithm for 6PolSK-QPSK signals would be provided.

The object of the present invention is to provide improved concepts for determining phase noise estimates. The object of the present invention is solved by an apparatus according to claim 1, by a method according to claim 17 and by a computer program according to claim 18.

An apparatus for determining a first and a second phase noise estimate is provided.

The apparatus comprises a receiving interface, a partitioning module, a polarization decision module, a phase rotation module and a determination module.

The receiving interface is configured to receive a plurality of input samples of an input sequence. The partitioning module is configured to classify the input samples of the input sequence into two or more sets. The polarization decision module is configured to decide for some of the input samples, whether to modify either the first amplitude value of the first polarization-component sample or the second amplitude value of the second polarization-component sample. The phase rotation module is configured to determine a member sample group comprising a plurality of member samples, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of some of the input samples. The determination module is configured to determine the first phase noise estimate based on the first polarization-component sample of each member sample of the member sample group and the second phase noise estimate based on the second polarization-component sample of each member sample of the member sample group.

In particular, in an embodiment, the apparatus for determining a first and a second phase noise estimate comprises a receiving interface for receiving a plurality of input samples of an input sequence, wherein each input sample of the plurality of input samples comprises a first polarization-component sample indicating a first complex value, and a second polarization-component sample indicating a second complex value. A first amplitude value and a first phase value are assigned to said first polarization-component sample. Said first amplitude value is the amplitude of said first complex value. Said first phase value is the phase of said first complex value. A second amplitude value and a second phase value are assigned to said second polarization-component sample. Said second amplitude value is the amplitude of said second complex value. Said second phase value is the phase of said second complex value.

Furthermore, the apparatus comprises a partitioning module for classifying the input samples of the input sequence into two or more sets by assigning each input sample of the input sequence to exactly one of the two or more sets depending on the first polarization-component sample of said input sample and depending on the second polarization-component sample of said input sample.

Moreover, the apparatus comprises a polarization decision module for deciding for each input sample of the input samples of a second set of the two or more sets, whether to modify either the first amplitude value of the first polarization-component sample or the second amplitude value of the second polarization-component sample of said input sample, depending on the first amplitude value of the first polarization-component sample and the second amplitude value of the second polarization-component sample of said input sample, and for modifying either said first amplitude value of said first polarization-component sample or said second amplitude value of said second polarization-component sample.

Furthermore, the apparatus comprises a phase rotation module for determining a member sample group comprising a plurality of member samples. The phase rotation module is configured to determine a plurality of modified samples by modifying each of the input samples of a first set of the two or more sets, being different from the second set of the two or more sets, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of said input sample to obtain one of the plurality of modified samples. The phase rotation module is configured to determine the member sample group so that the member sample group comprises each modified sample of the plurality of modified samples as one of the member samples. The phase rotation module is configured to not modify any of the input samples of the second set of the two or more sets. Moreover, the phase rotation module is configured to determine the member sample group so that the member sample group comprises furthermore each of the input samples of said second set as a further one of the member samples.

Moreover, the apparatus comprises a determination module for determining the first phase noise estimate based on the first polarization-component sample of each member sample of the member sample group, and for determining the second phase noise estimate based on the second polarization-component sample of each member sample of the member sample group.

According to an embodiment, the determination module may be configured to determine a first intermediate sample value for each member sample of the member sample group by raising the first complex value indicated by the first polarization-component sample of said member sample to the $4^{th}$ power. The determination module may be configured to determine the first phase noise estimate in dependence of a first sum of the first intermediate sample values of the member samples of the member sample group. Moreover, the determination module may be configured to determine a second intermediate sample value for each member sample of the member sample group by raising the second complex value indicated by the second polarization-component sample of said member sample to the $4^{th}$ power. Furthermore, the determination module may be configured to determine the first phase noise estimate in dependence of a second sum of the second intermediate sample values of the member samples of the member sample group.

In an embodiment, the determination module may be configured to determine the first phase noise estimate based on the formula:

$$\sum_{q=1}^{N} Z^4{}_{x,k} + C \cdot Z^4{}_{y,k}$$

wherein k indicates an index of one of the member samples of the member samples group, wherein x indicates a first polarization, wherein $Z^4{}_{x,k}$ indicates the first intermediate sample value of said one member sample of the member sample group, wherein y indicates a second polarization, wherein $Z^4{}_{y,k}$ indicates the second intermediate sample value of said one member sample of the member sample group, wherein C is a coupling factor with $0 \leq C \leq 1$, and wherein N indicates the number of member samples of the member sample group.

According to another embodiment, the determination module may be configured to determine the first phase noise estimate according to the formula:

$$\psi_{x,i} = \frac{1}{4} \arg \left[ \sum_{q=1}^{N} Z^4{}_{x,k} + C \cdot Z^4{}_{y,k} \right]$$

wherein $\psi_{x,i}$ is the first noise estimate.

In an embodiment, the determination module may be configured to determine the second phase noise estimate according to the formula:

$$\psi_{y,i} = \frac{1}{4} \arg \left[ \sum_{q=1}^{N} Z^4{}_{y,k} + C \cdot Z^4{}_{x,k} \right]$$

wherein $\psi_{y,i}$ is the second noise estimate,

wherein $Z^4{}_{y,k}$ indicates one of the second intermediate sample values, wherein $0 \leq C \leq 1$, and wherein N indicates the number of member samples of the member sample group.

According to an embodiment, the phase rotation module may be configured to determine the modified samples by modifying the first and the second polarization-component sample of each of the input samples of the first set of the two or more sets by applying a phase rotation of $\pi/4$ to the first polarization-component sample and the second polarization-component sample of said input sample.

In another embodiment, the partitioning module may be configured to classify the input samples of the input sequence into two or more subsets. The partitioning module may be configured to determine for each input sample an error value for each of the two or more subsets based on the first polarization-component sample and the second polarization-component sample of said input sample and based on the first predefined polarization and the second predefined polarization value of said subset. Moreover, the partitioning module may be configured to assign said input sample to the subset with the smallest error value. Furthermore, the partitioning module may be configured to classify the input samples of the input sequence into the two or more sets such that for each subset of the two or more subsets all input samples of said subset are assigned to the same set of the two or more sets.

According to an embodiment, the partitioning module may be configured to determine for each input sample the error value for each of the two or more subsets based on the formula:

$$\varepsilon_{k,l} = \left(|Z_{x,k}|^2 - |S_{x,l}|^2\right)^2 + \left(|Z_{y,k}|^2 - |S_{y,l}|^2\right)^2 ,$$

wherein $k$ indicates one of the input samples of the input sequence, wherein $l$ indicates one of the subsets, wherein $\varepsilon_{k,l}$ is the error value for the $k$-th input sample and the $l$-th subset, wherein x indicates the first polarization, wherein y indicates the second polarization, wherein $|Z_{x,k}|$ indicates the first amplitude value of the first polarization-component sample of the $k$-th input sample, wherein $|Z_{y,k}|$ indicates the second amplitude value of the second polarization-component sample of the $k$-th input sample, wherein $|S_{x,l}|$ indicates the first predefined polarization value of the $l$-th subset and wherein $|S_{y,l}|$ indicates the second predefined polarization value of the $l$-th subset.

In an embodiment, the partitioning module may be configured to classify the input samples of the input sequence into exactly three subsets as the two or more subsets, and wherein the first predefined polarization value of a first one of the subsets is $\sqrt{2}$, wherein the second predefined polarization value of the first one of the subsets is $\sqrt{2}$, wherein the first predefined polarization value of a second one of the subsets is 2, wherein the second predefined polarization value of the second one of the subsets is 0, wherein the first predefined polarization value of a third one of the subsets is 0, and wherein the second predefined polarization value of the third one of the subsets is 2. The partitioning module may be configured to classify the input samples of the input sequence into the two or more sets such that all input samples of the first subset are comprised by the first one of the two or more sets and such that all input samples of the second subset and of the third subset are assigned to the second one of the two or more sets.

According to another embodiment, the polarization decision module may be configured to modify for each input sample of the input samples of the at least one of the sets the first amplitude value of the first polarization-component sample of said input sample when the first amplitude value of the first polarization-component sample of said input sample is smaller than the second amplitude value of the second polarization-component sample of said input sample to obtain a first modified amplitude value of the first polarization-component sample of said input sample, so that the first modified amplitude value of said first polarization-component sample is smaller than said first amplitude value of said first polarization-component sample. Moreover, the polarization decision module may be configured to modify for each input sample of the input samples of the at least one of the sets the second amplitude value of the second polarization-component sample of said input sample when the second amplitude value of the second polarization-component sample of said input sample is smaller than the first amplitude value of the first polarization-component sample of said input sample to obtain a second modified amplitude value of the second polarization-component sample of said input sample, so that the second modified amplitude value of said second polarization-component sample is smaller than said second amplitude value of said second polarization-component sample.

In a further embodiment, the polarization decision module may be configured to modify for each input sample of the input samples of the second set of the two or more sets, the first amplitude value of the first polarization-component sample of said input sample when the first amplitude value of the first polarization-component sample of said input sample is smaller than the second amplitude value of the second polarization-component sample of said input sample to obtain a first modified amplitude value of the first polarization-component sample of said input sample, so that the first modified amplitude value of said first polarization-component sample is smaller than said first amplitude value of said first polarization-component sample. Moreover, the polarization decision module may be configured to modify for each input sample of the input samples of the second set of the two or more sets, the second amplitude value of the second polarization-component sample of said input sample when the first amplitude value of the first polarization-component sample of said input sample is greater than or equal to the second amplitude value of the second polarization-component sample of said input sample to obtain a second modified amplitude value of the second polarization-component sample of said input sample, so that the second modified amplitude value of said second polarization-component sample is smaller than said second amplitude value of said second polarization-component sample. Furthermore, the polarization decision module may be configured to not modify the amplitude value of the first polarization-component sample of any of the input samples of a set of the two or more sets, being different from the second set of the two or more sets. Moreover, the polarization decision module may be configured to not modify the amplitude value of the second polarization-component sample of any of the input samples of a set of the two or more sets, being different from the second set of the two or more sets.

According to another embodiment, the receiving interface may comprise one or more demultiplexing units for demultiplexing at least some of the samples of the input sequence such that the samples are demultiplexed for parallel processing.

According to an embodiment, the determination module may comprise a weighting module being configured to determine a plurality of weighted values. The weighting module may be configured to determine each of the plurality of weighted values by multiplying the first polarization-component samples or the second polarization-component samples of at least two of the member samples of the member sample group by a weight. The determination module may be configured to determine the first phase noise estimate and the second phase noise estimate based at least some of the plurality of weighted values.

In an embodiment, the above-described apparatus may be configured to determine the first and the second phase noise estimate being phase noise estimates of an optically transmitted signal comprising symbols being modulated by employing a 6-ary polarization-shift keying quadrature phase-shift keying format.

Moreover, an apparatus for phase correction is provided. The apparatus for phase correction comprises an apparatus according to one of the above-described embodiments for determining a first and a second phase noise estimate based on one or more input samples. Furthermore, the apparatus for phase correction comprises a phase correction module for conducting phase correction on the one or more input samples based on the one or more phase noise estimates.

In some embodiments, the above-described embodiments of the present invention may be implemented as an application specific integrated circuit (ASIC).

Moreover, a method for determining a first and a second phase noise estimate is provided. The method comprises:

- Receiving a plurality of input samples, wherein each input sample of the plurality of input samples comprises a first polarization-component sample, indicating a first complex value, and a second polarization-component sample, indicating a second complex value, wherein a first amplitude value and a first phase value is assigned to said first polarization-component sample, wherein said first amplitude value is the amplitude of said first complex value, wherein said first phase value is the phase of said first complex value, wherein a second amplitude value and a second phase value is assigned to said second polarization-component sample, wherein said second amplitude value is the amplitude of said second complex value, and wherein said second phase value is the phase of said second complex value,

- Assigning at least some input samples of the plurality of input samples to an input sequence,

- Classifying the input samples of the input sequence into two or more sets by assigning each input sample of the input sequence to exactly one of the two or more sets depending on the first polarization-component sample of said input sample and depending on the second polarization-component sample of said input sample,

- Deciding for each input sample of the input samples of a second one of the sets, whether to modify either the first amplitude value of the first polarization-component sample or the second amplitude value of the second polarization-component sample of said input sample, depending on the first amplitude value of the first polarization-component sample and the second amplitude value of the second polarization-component sample of said input sample, and for modifying either said first amplitude value of said first polarization-component sample or said second amplitude value of said second polarization-component sample,

- Determining a member sample group comprising a plurality of member samples, wherein the step of determining the member sample group comprises determining a plurality of modified samples by modifying each of the input samples of a first set of the two or more sets, being different from the second set of the two or more sets, by applying a phase rotation of the first polarization-component sample and the second polarization-component sample of said input sample to obtain one of the plurality of modified samples, wherein the member sample group is determined so that the member sample group comprises each modified sample of the plurality of modified samples as one of the member samples, wherein the step of determining the member sample group comprises to not modify any of the input samples of the second set of the two or more sets, wherein the member sample group is determined so that the member sample group comprises furthermore each of the input samples of said first set as further one of the member samples,

- Determining the first phase noise estimate based on the first polarization-component sample of each member sample of the member sample group. And:

- Determining the second phase noise estimate based on the second polarization-component sample of each member sample of the member sample group.

Furthermore, a computer program for implementing the above-described method when being executed on a computer or signal processor is provided.

In the following, embodiments of the present invention are described in more detail with reference to the figures, in which:

Fig. 1 illustrates an apparatus for determining a first and a second phase noise estimate according to an embodiment,

Fig. 2 illustrates an apparatus for determining a first and a second phase noise estimate according to another embodiment,

Fig. 3 illustrates an apparatus for phase correction according to an embodiment,

Fig. 4 illustrates an apparatus for phase correction according to another embodiment,

Fig. 5a illustrates an apparatus for determining a first and a second phase noise estimate according to another embodiment,

Fig. 5b illustrates an apparatus for phase correction according to a further embodiment,

Fig. 6 illustrates an apparatus for phase correction according to another embodiment,

Fig. 7 (a) illustrates a constellation diagram of a 6PolSK-QPSK signal; (b) illustrates the corresponding time-resolved states of polarization on the Poincaré sphere, and

Fig. 8 illustrates a constellation diagram of one polarization tributary of a received 126-Gb/s 6PolSK-QPSK signal at 30 dB optical signal-to-noise ratio with a laser linewidth of ~ 100kHz, (a) before phase correction and (b) after phase correction.

Fig. 1 illustrates an apparatus for determining a first and a second phase noise estimate according to an embodiment.

The apparatus comprises a receiving interface 110, a partitioning module 120, a polarization decision module 130, a phase rotation module 140 and a determination module 150.

The receiving interface 110 is configured to receive a plurality of input samples of an input sequence. The partitioning module 120 is configured to classify the input samples of the input sequence into two or more sets. The polarization decision module 130 is configured to decide for some of the input samples, whether to modify either the first amplitude value of the first polarization-component sample $Z_{x,k}$ or the second amplitude value of the second polarization-component sample $Z_{y,k}$. The phase rotation module 140 is configured to determine a member sample group comprising a plurality of member samples, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of said input sample. The determination module 150 is configured to determine the first phase noise estimate based on the first polarization-component sample $Z_{x,k}$ of each member sample of the member sample group and the second phase noise estimate based on the second polarization-component sample $Z_{y,k}$ of each member sample of the member sample group.

In particular, in an embodiment, the apparatus for determining a first and a second phase noise estimate comprises the receiving interface 110 for receiving a plurality of input samples of an input sequence (e.g. input sequence *i*), wherein each input sample of the plurality of input samples comprises a first polarization-component sample $Z_{x,k}$ indicating a first complex value, and a second polarization-component sample $Z_{y,k}$ indicating a second complex value. A first amplitude value and a first phase value are assigned to said first polarization-component sample $Z_{x,k}$. Said first amplitude value is the amplitude of said first complex value. Said first phase value is the phase of said first complex value. A second amplitude value and a second phase value are assigned to said second polarization-component sample $Z_{y,k}$. Said second amplitude value is the amplitude of said second complex value. Said second phase value is the phase of said second complex value.

Furthermore, the apparatus comprises the partitioning module 120 for classifying the input samples of the input sequence into two or more sets (e.g. set $C_1$ and set $C_2$) by assigning each input sample of the input sequence to exactly one of the two or more sets depending on the first polarization-component sample $Z_{x,k}$ of said input sample and depending on the second polarization-component sample $Z_{y,k}$ of said input sample.

Moreover, the apparatus comprises the polarization decision module 130 for deciding for each input sample of the input samples of a second set (e.g. the set $C_2$) of the two or more sets, whether to modify either the first amplitude value of the first polarization-component sample $Z_{x,k}$ or the second amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample, depending on the first amplitude value of the first polarization-component sample $Z_{x,k}$ and the second amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample, and for modifying either said first amplitude value of said first polarization-component sample $Z_{x,k}$ or said second amplitude value of said second polarization-component sample $Z_{y,k}$.

Furthermore, the apparatus comprises the phase rotation module 140 for determining a member sample group comprising a plurality of member samples. The phase rotation module 140 is configured to determine a plurality of modified samples by modifying each of the input samples of a first set (e.g. the set $C_1$) of the two or more sets, being different from the second set (e.g. set $C_2$) of the two or more sets, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of said input sample. Moreover, the phase rotation module 140 is configured to determine the member sample group so that the member sample group comprises each modified sample of the plurality of modified samples as one of the member samples. Furthermore, the phase rotation module 140 is configured to not modify any of the input samples of the second set (e.g. set $C_2$) of the two or more sets. Moreover, the phase rotation module 140 is configured to determine the member sample group so that the member sample group comprises furthermore each of the input samples of said second set (e.g. set $C_2$) as a further one of the member samples.

Moreover, the apparatus comprises the determination module 150 for determining the first phase noise estimate (e.g. $\psi_{x,i}$ ) based on the first polarization-component sample $Z_{x,k}$ of each member sample of the member sample group, and for determining the second phase noise estimate (e.g. $\psi_{y,i}$ ) based on the second polarization-component sample $Z_{y,k}$ of each member sample of the member sample group.

In the following, particular embodiments are described.

Fig. 2 illustrates an apparatus for determining a first and a second phase noise estimate according to another embodiment.

The apparatus illustrated by Fig. 2 comprises a receiving interface 210, a partitioning module 220, a polarization decision module 230, a phase rotation module 240 and a determination module 250.

The receiving interface 210 receives the plurality of input samples as samples of an input sequence. Each of the input samples comprises a first polarization-component sample $Z_{x,k}$ and a the second polarization-component sample $Z_{y,k}$.

The receiving interface 210 comprises a first demultiplexing unit 212 and a second demultiplexing unit 214 for demultiplexing the input sequence such that the samples are demultiplexed for parallel processing. The first demultiplexing unit 212 receives the first polarization-component sample $Z_{x,k}$ of each of the input samples. Here, x denotes a first polarization and k denotes the k-th sample of the sample sequence. The second demultiplexing unit 214 receives the second polarization-component sample $Z_{y,k}$ of each of the input samples. Here, y denotes a second polarization and k denotes the k-th sample of the sample sequence.

The partitioning module 220, the polarization decision module 230 and the phase rotation module 240 of Fig. 2 may correspond to the partitioning module 120, the polarization decision module 130 and the phase rotation module 140 of Fig. 1, respectively.

The determination module 250 represents a particular embodiment of a determination module.

In Fig. 2, the receiving interface receives a plurality of input samples, which may be considered as samples of an input sequence. Each of the input samples comprises a first polarization-component sample $Z_{x,k}$ and a second polarization-component sample $Z_{y,k}$. The first polarization-component sample $Z_{x,k}$ is a complex value and the second polarization-component sample $Z_{y,k}$ is also a complex value. k indicates that $Z_x$,k and $Z_{y,k}$ are the first and the second polarization-component sample of the k-th sample of the sample sequence. Moreover, the first polarization-component samples $Z_{x,k}$ of the input samples of the sample sequence form themselves a first complex sample sequence. Furthermore, the second polarization-component samples $Z_{y,k}$ of the input samples of the sample sequence form themselves a second complex sample sequence.

The incoming first and second complex sample sequences, e.g., from a polarization-diversity coherent receiver at the input of a CPE unit are expressed as:

$$Z_{p,k} = R\sqrt{P_{lo}P_s} \cdot A_{p,k} \cdot e^{j(\theta_{p,k}+\varphi_{p,k})} + n_{p,k}$$

where $p \in \{x, y\}$ is the polarization, wherein $k$ is an index identifying the *k-th* sample of the first or second complex sample sequence, respectively, wherein R is the responsivity of the photodiodes, and wherein $P_{lo}$ and $P_s$ represent the average powers of local oscillator and signal respectively. $A_{p,k} \in \{0, \sqrt{2}, 2\}$ and $\theta_{p,k} = m\pi/4$ with $m \in \{0, 1, 2, 3, \ldots, 7\}$ are the signal information amplitude and phase, respectively. $\varphi_{p,k}$ is the phase noise and $n_{p,k}$ represents the additive noise.

The polarization-component samples $Z_{p,k}$ are first demultiplexed into blocks with N samples per block. Each of the blocks is also referred to as a “input sequence”. With respect to the i-th block (input sequence), $k$ is defined as $k = q + (i - 1)N$ with $q \in \{1, 2, \ldots, N\}$. In the embodiment of Fig. 2, it is assumed that a number of $N$ input samples are processed in parallel. Therefore, this approach is referred to as block scheme. Each of the N input samples comprises a first polarization-component sample $Z_{x,k}$ and a second polarization-component sample $Z_{y,k}$.

The partitioning module 220 is configured to classify the input samples of the input sequence into two or more subsets, e.g. three subsets $S_1$, $S_2$, $S_3$.

A first predefined polarization value and a second polarization value is assigned to each subset of the two or more subsets. For example, the first predefined polarization value $|S_{x,1}|$ and the second predefined polarization value $|S_{y,1}|$ of the subset $S_1$ may be

$S_1$: $|S_{x,l}| = \sqrt{2}$ and $|S_{y,l}| = \sqrt{2}$ ,

the first predefined polarization value $|S_{xl}|$ and the second predefined polarization value $|S_{y,l}|$ of the subset $S_2$ may be

$S_2$: $|S_{x,l}| = 2$ and $|S_{y,l}| = 0$ ,

and the first predefined polarization value $|S_{x,l}|$ and the second predefined polarization value $|S_{y,l}|$ of the subset $S_3$ may be

$S_3$: $|S_{x,l}| = 0$ and $|S_{y,l}| = 2$ ,

The partitioning module 220 is configured to determine for each input sample an error value $\varepsilon_{k,l}$ for each of the two or more subsets, e.g. the subsets $S_1$, $S_2$, $S_3$, based on the first polarization-component sample and the second polarization-component sample of said input sample and based on the first predefined polarization value and the second predefined polarization value of said subset $S_1$, $S_2$, $S_3$.

Moreover, the partitioning module 220 is configured to assign said input sample to the subset $S_1$, $S_2$ or $S_3$ for which the smallest error value has been determined.

Furthermore, the partitioning module 220 is configured to classify the input samples of the input sequence into two or more sets, e.g. the sets $C_1$ and $C_2$, such that for each subset $S_1$, $S_2$, $S_3$ of the two or more subsets all input samples of said subset are comprised by the same set of the two or more sets $C_1$, $C_2$.

For example, in a particular embodiment, in the partitioning module 220 (the set partitioning stage), the input samples are classified into the three subsets $S_1$, $S_2$ and $S_3$ of complex samples. For the polarization values assigned to the three sets $S_1$, $S_2$ and $S_3$, the following is defined:

$S_1$: $|S_{x,l}| = \sqrt{2}$ and $|S_{y,l}| = \sqrt{2}$ ,

$S_2$: $|S_{x,l}| = 2$ and $|S_{y,l}| = 0$ ,

$S_3$: $|S_{x,l}| = 0$ and $|S_{y,l}| = 2$ .

By calculating the squared error jointly in both polarizations

$$\varepsilon_{k,l} = \left(|Z_{x,k}|^2 - |S_{x,l}|^2\right)^2 + \left(|Z_{y,k}|^2 - |S_{y,l}|^2\right)^2,$$

where $l \in \{1, 2, 3\}$,

the error value $\varepsilon_{k,l}$ is obtained for each of the input samples and for each of the three subsets. (A particular input sample is identified by index $k$ and a particular subset is identified by index $l$.)

The partitioning module 220 is configured to assign said input sample identified by index $k$ to the subset $S_1$, $S_2$ or $S_3$ with the smallest error value $\varepsilon_{k,l}$.

Moreover, for the embodiment illustrated by Fig. 2, it is defined that the subset $S_1$ is identical with set $C_1$, while the subsets $S_2$ and $S3$ are subsets of set $C_2$.

Therefore,

$\{Z_{x,k}; Z_{y,k}\} \in C_1$ when $\varepsilon_{k,1} = \min(\varepsilon_{k,l})$ and

$\{Z_{x,k}; Z_{y,k}\} \in C_2$ when $\varepsilon_{k,2} = \min(\varepsilon_{k,l})$ or $\varepsilon_{k,3} = \min(\varepsilon_{k,l})$

wherein $\{Z_{x,k}; Z_{y,k}\}$ denotes the k-th input sample comprising a first polarization-component sample $Z_{x,k}$ and a second polarization-component sample $Z_{y,k}$.

According to this definition, the partitioning module 220 is configured to classify the input samples into the two sets $C_1$, $C_2$, such that all input samples of the first subset $S_1$ are comprised by the first one $C_1$ of the two or more sets and such that all input samples of the second subset $S_2$ and of the third subset $S_3$ are assigned to the second one $C_2$ of the two or more sets.

The input samples belonging to the set $C_2$ are then fed into the polarization decision module 230. This polarization decision module 230 compares the amplitude $Z_{x,k}$ of the first polarization-component sample (x-polarization) of each of the input samples of set $C_2$ with the amplitude $Z_{y,k}$ of the second polarization-component sample (y-polarization) of said input sample.

This polarization decision module 230 decides in favor of polarization-component samples having larger amplitude and suppresses the amplitude of the polarization-component samples in the orthogonal polarization to zero, e.g. if $Z_{x,k} \geq Z_{y,k}$ then $Z_{y,k}$ is set to zero, else if $Z_{x,k} < Z_{y,k}$ then $Z_{x,k}$ is set to zero. This operation ensures that for symbols belonging to the set $C_2$, only the polarization tributary with a valid QPSK signal state is used for estimation of the carrier phase.

Generally speaking, wherein the polarization decision module 230 is configured to modify for each input sample of the input samples of the at least one of the sets, e.g. the set $C_2$, the first amplitude value of the first polarization-component sample $Z_{x,k}$ of said input sample when the first amplitude value of the first polarization-component sample $Z_{x,k}$ of said input sample is smaller than the second amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample to obtain a first modified amplitude value of the first polarization-component sample $Z_{x,k}$ of said input sample, so that the first modified amplitude value of said first polarization-component sample $Z_{x,k}$ is smaller than said first amplitude value of said first polarization-component sample $Z_{x,k}$.

Moreover, the polarization decision module 230 is configured to modify for each input sample of the input samples of the at least one of the sets, e.g. the set $C_2$, the second amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample when the second amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample is smaller than the first amplitude value of the first polarization-component sample $Z_{x,k}$ of said input sample to obtain a second modified amplitude value of the second polarization-component sample $Z_{y,k}$ of said input sample, so that the second modified amplitude value of said second polarization-component sample $Z_{y,k}$ is smaller than said second amplitude value of said second polarization-component sample $Z_{y,k}$.

In the phase rotation module 240, a $\pi/4$ phase rotation is applied to the first and the second polarization-component sample of all input samples belonging to the set $C_1$.

By this, the input samples of the set $C_1$ are modified. The phase rotation module now forms a member sample group which comprises as member samples all the (modified) input samples of the set $C_1$, and all the input samples of the set $C_2$, which have not been modified by the phase rotation module 240 (but possibly by the polarization decision module 230).

The determination module 250 is configured to determine a first intermediate sample value for each member sample of the member sample group by raising the first complex value indicated by the first polarization-component sample of said member sample to the 4th power. The determination module 250 is configured to determine the first phase noise estimate in dependence of a first sum of the first intermediate sample values of the member samples of the member sample group. For example, the first sum of the first intermediate values may be:

$$\sum_{q=1}^{N} Z^4{}_{x,k}$$

Moreover, the determination module 250 may be configured to determine a second intermediate sample value for each member sample of the member sample group by raising the second complex value indicated by the second polarization-component sample of said member sample to the 4th power. Furthermore, the determination module may be configured to determine the first phase noise estimate in dependence of a second sum of the second intermediate sample values of the member samples of the member sample group. For example, the second sum of the second intermediate values may be:

$$\sum_{q=1}^{N} Z^4{}_{y,k}$$

For example, the determination module 250 may employ a conventional M-th power feed-forward carrier phase estimation stage.

The complex symbols of the i-th block may be raised to the 4-th power in order to remove the QPSK modulation and averaging over $N$ samples is performed.

In other words, the determination module 250 may raise the first polarization component sample and the second polarization-component sample of each member sample of the member sample group to the 4-th power in order to remove the QPSK modulation and averaging over $N$ samples is performed.

Both polarizations are contaminated by the same laser phase noise. Therefore, the phase noise in x- and y-polarization is highly correlated in the absence of nonlinear impairments.

Consequently, coupling the phase noise information between both polarizations can enhance the performance of the algorithm (see [6]).

The phase noise estimates in both polarizations are coupled by the determination module 250 after being weighted by a coupling factor of $0 \leq C \leq 1$, where $C = 0$ results in no coupling at all and $C = 1$ results in the same phase noise estimate in both polarizations.

The determination module 250 then divides the phase of the averaged signal by four, resulting in the phase noise estimates for x- and y-polarization $\psi_x$, $\psi_y$ for the i-th block:

$$\psi_{x,i} = \frac{1}{4} \arg\left[\sum_{q=1}^{N} Z^4{}_{x,k} + C \cdot Z^4{}_{y,k}\right]$$

$$\psi_{y,i} = \frac{1}{4} \arg\left[\sum_{q=1}^{N} Z^4{}_{y,k} + C \cdot Z^4{}_{x,k}\right],$$

The phase noise estimates $\psi_{x,i}$ and $\psi_{y,i}$ lie inside the interval [ -π/4 , π/4 ] due to the argument function.

An apparatus according to a specific embodiment may be configured to determine the first and the second phase noise estimate which are phase noise estimates of an optically transmitted signal comprising symbols being modulated by employing a 6-ary polarization-shift keying quadrature phase-shift keying format.

Fig. 3 illustrates an apparatus for phase correction according to an embodiment. The apparatus for phase correction comprises an apparatus 310 according to one of the above-described embodiments for determining a first and a second phase noise estimate based on one or more input samples. Furthermore, the apparatus for phase correction comprises a phase correction module 320 for conducting phase correction on the one or more input samples of the sample sequence based on the one or more phase noise estimates to obtain one or more phase-corrected input samples.

Fig. 4 illustrates an apparatus for phase correction according to another embodiment. Again, the apparatus for phase correction comprises an apparatus 310 according to one of the above-described embodiments for determining a first and a second phase noise estimate based on one or more input samples. Furthermore, again, the apparatus for phase correction comprises a phase correction module 320 for conducting phase correction on the one or more input samples of the sample sequence based on the one or more phase noise estimates.

In particular, Fig. 4 illustrates a block diagram of the 6Pol-QPSK joint-polarization carrier phase estimation using a block scheme according to an embodiment.

As already explained, the phase noise estimates $\psi_{x,i}$ and $\psi_{y,i}$ lie inside the interval [ $-\pi/4$ , $\pi/4$ ] due to the argument function. However, the phase noise is a Wiener process ranging from $-\infty$ to $+\infty$. Therefore, phase unwrapping is applied in order to restore the original phase noise trajectory. After that, the estimated phase noise is used to correct the phase of the received symbols in the corresponding block. Samples belonging to the set $C_1$ are rotated back by applying a $\pi/4$ phase shift.

In Fig. 4, each of the phase corrected input samples comprises the corresponding first and second polarization-component samples $Z'_{x,k}$ and $Z'_{y,k}$.

In the following, a further embodiment is provided, which is a variant of the above-described embodiments.

Fig. 5a illustrates an apparatus for determining a first and a second phase noise estimate according to a further embodiment which implements such a variant. The apparatus comprises a receiving interface (not shown), a partitioning module 220, a polarization decision module 230, a phase rotation module 240 and a determination module 250.

The alternative approach described with reference to Fig. 5a is an alternative approach that could be used works symbol by symbol and is referred to as "sliding window scheme". Generally, this approach improves the phase estimation accuracy at the expense of increasing hardware complexity.

The apparatus of Fig. 5a is configured to execute the set partitioning first and then the polarization decision is applied if the sample belongs to the set $C_2$, or a $\pi/4$ phase rotation is applied if the sample belongs to the set $C_1$. Afterwards, averaging over $2N+1$ samples is performed in order to smooth out additive noise using a windowing function. Different window functions could be implemented to obtain more accurate estimation, e.g. Wiener, hyperbolic, sinc, etc.

In particular, regarding the apparatus of Fig. 5a, the determination module 250 comprises a weighting module 252 which is configured to determine a plurality of weighted values. The weighting module 252 is configured to determine each of the plurality of weighted values by multiplying the first polarization-component samples or the second polarization-component samples of at least two of the member samples of the member sample group and a weight. The weight may, for example, be a complex number. The determination module 250 is configured to determine the first phase noise estimate and the second phase noise estimate based at least some of the plurality of average values.

For example, weighting module 252 applies the window function on the 2N + 1 samples. Each sample may, for example, be weighted by the window function. In a particular embodiment, the window function may, for example, be rectangular, e.g. all samples may be multiplied by a constant number, e.g. all samples may be multiplied by 1. In other embodiments, arbitrary other window functions may be employed, e.g. a hyperbolic function, a sinc function or a complex window function.

Fig. 5b illustrates an apparatus for phase correction according to a further embodiment. The apparatus for phase correction according to Fig. 5b comprises the apparatus 510 for determining a first and a second phase estimation of Fig. 5a the determination module of which comprises the weighting module 252. Furthermore, the apparatus for phase correction of Fig. 5b comprises a phase correction module 320 for conducting phase correction on the one or more input samples of the sample sequence based on the one or more phase noise estimates to obtain one or more phase-corrected input samples.

In particular, Fig. 5b illustrates a block diagram of the 6PolSK-QPSK point-polarization carrier phase estimation using a sliding window scheme for averaging. The index $k$ refers to *k-th* sample and $q \in \{1, 2, ..., N\}$. The value $N$ denotes the length of the moving average filter. In Fig. 5b, each of the phase corrected input samples comprises the corresponding first and second polarization-component samples $Z''_{x,k}$ and $Z''_{y,k}$.

Moreover, Fig. 6 illustrates an apparatus for phase correction according to another embodiment. In particular, Fig. 6 illustrates a block diagram of the 6Pol-QPSK carrier phase estimation without coupling process between the two polarization tributaries.

In Fig. 6, each of the phase corrected input samples comprises the corresponding first and second polarization-component samples $Z'_{x,k}$ and $Z'_{y,k}$.

In some embodiments, the above-described embodiments of the present invention may be implemented as an application specific integrated circuit (ASIC).

Although some aspects have been described in the context of an apparatus, it is clear that these aspects also represent a description of the corresponding method, where a block or device corresponds to a method step or a feature of a method step. Analogously, aspects described in the context of a method step also represent a description of a corresponding block or item or feature of a corresponding apparatus.

The inventive decomposed signal can be stored on a digital storage medium or can be transmitted on a transmission medium such as a wireless transmission medium or a wired transmission medium such as the Internet.

Depending on certain implementation requirements, embodiments of the invention can be implemented in hardware or in software. The implementation can be performed using a digital storage medium, for example a floppy disk, a DVD, a CD, a ROM, a PROM, an EPROM, an EEPROM or a FLASH memory, having electronically readable control signals stored thereon, which cooperate (or are capable of cooperating) with a programmable computer system such that the respective method is performed.

Some embodiments according to the invention comprise a non-transitory data carrier having electronically readable control signals, which are capable of cooperating with a programmable computer system, such that one of the methods described herein is performed.

Generally, embodiments of the present invention can be implemented as a computer program product with a program code, the program code being operative for performing one of the methods when the computer program product runs on a computer. The program code may for example be stored on a machine readable carrier.

Other embodiments comprise the computer program for performing one of the methods described herein, stored on a machine readable carrier.

In other words, an embodiment of the inventive method is, therefore, a computer program having a program code for performing one of the methods described herein, when the computer program runs on a computer.

A further embodiment of the inventive methods is, therefore, a data carrier (or a digital storage medium, or a computer-readable medium) comprising, recorded thereon, the computer program for performing one of the methods described herein.

A further embodiment of the inventive method is, therefore, a data stream or a sequence of signals representing the computer program for performing one of the methods described herein. The data stream or the sequence of signals may for example be configured to be transferred via a data communication connection, for example via the Internet.

A further embodiment comprises a processing means, for example a computer, or a programmable logic device, configured to or adapted to perform one of the methods described herein.

A further embodiment comprises a computer having installed thereon the computer program for performing one of the methods described herein.

In some embodiments, a programmable logic device (for example a field programmable gate array) may be used to perform some or all of the functionalities of the methods described herein. In some embodiments, a field programmable gate array may cooperate with a microprocessor in order to perform one of the methods described herein. Generally, the methods are preferably performed by any hardware apparatus.

The above described embodiments are merely illustrative for the principles of the present invention. It is understood that modifications and variations of the arrangements and the details described herein will be apparent to others skilled in the art. It is the intent, therefore, to be limited only by the scope of the impending patent claims and not by the specific details presented by way of description and explanation of the embodiments herein.

## References

[1] H. Bülow, "Polarization QAM modulation (POL-QAM) for coherent detection schemes," *Proc. Opt. Fiber Commun. Conf.,* Mar. 2009, paper OWG2.

[2] E. Agrell and M. Karlsson, "Power efficient modulation formals in coherent transmission systems," *J. Lightwave Technol.,* vol. 27, no. 22, pp. 5115–5126, Nov. 2009.

[3] H. Bülow, "Modulation scheme with increased number of states per polarization," US patent no. 8,073,338 B2, April 2009.

[4] A. J. Viterbi and A. M. Viterbi, "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," *IEEE Trans. Inf. Theory,* vol. IT-29, no. 4, pp. 543–551, Jul. 1983.

[5] T. Pfau, S. Hoffmann, and R. Noé, "Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations," *J. Lightwave Technol.,* vol. 27, no. 8, pp. 989–999, Apr. 2009

[6] M. Kuschnerov et al., "Joint-polarization carrier phase estimation for XPM-limited coherent polarization-multiplexed QPSK transmission with OOK-neighbors," in Proc. 34th *Eur. Conf Opt. Commun.,* Sept. 2008, paper Mo.4.D.2.

## Claims

1. An apparatus for determining a first and a second phase noise estimate, comprising:

a receiving interface (110; 210) for receiving a plurality of input samples of an input sequence, wherein each input sample of the plurality of input samples comprises a first polarization-component sample ($Z_{x,k}$) indicating a first complex value, and a second polarization-component sample ($Z_{y,k}$) indicating a second complex value, wherein a first amplitude value and a first phase value are assigned to said first polarization-component sample ($Z_{x,k}$), wherein said first amplitude value is the amplitude of said first complex value, wherein said first phase value is the phase of said first complex value, wherein a second amplitude value and a second phase value are assigned to said second polarization-component sample ($Z_{y,k}$), wherein said second amplitude value is the amplitude of said second complex value, and wherein said second phase value is the phase of said second complex value,

a partitioning module (120; 220) for classifying the input samples of the input sequence into two or more sets by assigning each input sample of the input sequence to exactly one of the two or more sets depending on the first polarization-component sample ($Z_{x,k}$) of said input sample and depending on the second polarization-component sample ($Z_{y,k}$) of said input sample,

a polarization decision module (130; 230) for deciding for each input sample of the input samples of a second set of the two or more sets, whether to modify either the first amplitude value of the first polarization-component sample ($Z_{x,k}$) or the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, depending on the first amplitude value of the first polarization-component sample ($Z_{x,k}$) and the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, and for modifying either said first amplitude value of said first polarization-component sample ($Z_{x,k}$) or said second amplitude value of said second polarization-component sample ($Z_{y,k}$),

a phase rotation module (140; 240) for determining a member sample group comprising a plurality of member samples, wherein the phase rotation module (140; 240) is configured to determine a plurality of modified samples by modifying each of the input samples of a first set of the two or more sets, being different from the second set of the two or more sets, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of said input sample to obtain one of the plurality of modified samples, wherein the phase rotation module (140; 240) is configured to determine the member sample group so that the member sample group comprises each modified sample of the plurality of modified samples as one of the member samples, wherein the phase rotation module (140; 240) is configured to not modify any of the input samples of the second set of the two or more sets, wherein the phase rotation module (140; 240) is configured to determine the member sample group so that the member sample group comprises furthermore each of the input samples of said second set as a further one of the member samples, and

a determination module (150; 250) for determining the first phase noise estimate based on the first polarization-component sample ($Z_{x,k}$) of each member sample of the member sample group, and for determining the second phase noise estimate based on the second polarization-component sample ($Z_{y,k}$) of each member sample of the member sample group.

2. An apparatus according to claim 1,

wherein the determination module (150; 250) is configured to determine a first intermediate sample value for each member sample of the member sample group by raising the first complex value indicated by the first polarization-component sample ($Z_{x,k}$) of said member sample to the $4^{th}$ power, and wherein the determination module (150; 250) is configured to determine the first phase noise estimate in dependence of a first sum of the first intermediate sample values of the member samples of the member sample group, and

wherein the determination module (150; 250) is configured to determine a second intermediate sample value for each member sample of the member sample group by raising the second complex value indicated by the second polarization-component sample ($Z_{y,k}$) of said member sample to the $4^{th}$ power, and wherein the determination module (150; 250) is configured to determine the first phase noise estimate in dependence of a second sum of the second intermediate sample values of the member samples of the member sample group.

3. An apparatus according to claim 2, wherein the determination module (150; 250) is configured to determine the first phase noise estimate based on the formula:

$$\sum_{q=1}^{N} Z^4{}_{x,k} + C \cdot Z^4{}_{y,k}$$

wherein k indicates an index of one of the member samples of the member samples group, wherein x indicates a first polarization, wherein $Z^4{}_{x,k}$ indicates the first intermediate sample value of said one member sample of the member sample group, wherein y indicates a second polarization, wherein $Z^4{}_{y,k}$ indicates the second intermediate sample value of said one member sample of the member sample group, wherein C is a coupling factor with $0 \leq C \leq 1$, and wherein N indicates the number of member samples of the member sample group.

4. An apparatus according to claim 3, wherein the determination module (150; 250) is configured to determine the first phase noise estimate according to the formula:

$$\psi_{x,i} = \frac{1}{4}\arg\left[\sum_{q=1}^{N} Z^4{}_{x,k} + C \cdot Z^4{}_{y,k}\right]$$

wherein $\psi_{x,i}$ is the first noise estimate.

5. An apparatus according to one of the preceding claims, wherein the determination module (150; 250) is configured to determine the second phase noise estimate according to the formula:

$$\psi_{y,i} = \frac{1}{4}\arg\left[\sum_{q=1}^{N} Z^4{}_{y,k} + C \cdot Z^4{}_{x,k}\right]$$

wherein $\psi_{y,i}$ is the second noise estimate,

wherein $Z^4{}_{y,k}$ indicates one of the second intermediate sample values, wherein $0 \leq C \leq 1$, and wherein N indicates the number of member samples of the member sample group.

6. An apparatus according to one of the preceding claims, wherein the phase rotation module (140; 240) is configured to determine the modified samples by modifying each of the input samples of the first set of the two or more sets by applying a phase rotation of $\pi/4$ to the first polarization-component sample and the second polarization-component sample of said input sample.

7. An apparatus according to one of the preceding claims,

wherein the partitioning module (120; 220) is configured to determine for each input sample an error value for each of the two or more subsets based on the first polarization-component sample ($Z_{x,k}$) and the second polarization-component sample ($Z_{y,k}$) of said input sample and based on the first predefined polarization value and the second predefined polarization value of said subset, and wherein the partitioning module (120; 220) is configured to assign said input sample to the subset with the smallest error value, and

wherein the partitioning module (120; 220) is configured to classify the input samples of the input sequence into the two or more sets such that for each subset of the two or more subsets all input samples of said subset are assigned to the same set of the two or more sets.

8. An apparatus according to claim 7,

wherein the partitioning module (120; 220) is configured to determine for each input sample the error value for each of the two or more subsets based on the formula

$$\varepsilon_{k,l} = \left(|Z_{x,k}|^2 - |S_{x,l}|^2\right)^2 + \left(|Z_{y,k}|^2 - |S_{y,l}|^2\right)^2,$$

wherein $k$ indicates one of the input samples of the input sequence, wherein $l$ indicates one of the subsets, wherein $\varepsilon_{k,l}$ is the error value for the $k$-th input sample and the $l$-th subset, wherein x indicates the first polarization, wherein y indicates the second polarization, wherein $|Z_{x,k}|$ indicates the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of the $k$-th input sample, wherein $|Z_{y,k}|$ indicates the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of the $k$-th input sample, wherein $|S_{x,l}|$ indicates the first predefined polarization value of the $l$-th subset and wherein $|S_{y,l}|$ indicates the second predefined polarization value of the $l$-th subset.

9. An apparatus according to claim 7 or 8,

wherein the partitioning module (120; 220) is configured to classify the input samples of the input sequence into exactly three subsets as the two or more subsets, and wherein the first predefined polarization value of a first one of the subsets is $\sqrt{2}$, wherein the second predefined polarization value of the first one of the subsets is $\sqrt{2}$, wherein the first predefined polarization value of a second one of the subsets is 2, wherein the second predefined polarization value of the second one of the subsets is 0, wherein the first predefined polarization value of a third one of the subsets is 0, and wherein the second predefined polarization value of the third one of the subsets is 2, and

wherein the partitioning module (120; 220) is configured to classify the input samples of the input sequence into the two or more sets such that all input samples of the first subset are assigned to first one of the two or more sets and such that all input samples of the second subset and of the third subset are assigned to the second one of the two or more sets.

10. An apparatus according to one of the preceding claims,

wherein the polarization decision module (130; 230) is configured to modify for each input sample of the input samples of the at least one of the sets the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample when the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample is smaller than the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample to obtain a first modified amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample, so that the first modified amplitude value of said first polarization-component sample ($Z_{x,k}$) is smaller than said first amplitude value of said first polarization-component sample ($Z_{x,k}$), and

wherein the polarization decision module (130; 230) is configured to modify for each input sample of the input samples of the at least one of the sets the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample when the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample is smaller than the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample to obtain a second modified amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, so that the second modified amplitude value of said second polarization-component sample ($Z_{y,k}$) is smaller than said second amplitude value of said second polarization-component sample ($Z_{y,k}$).

11. An apparatus according to one of the preceding claims,

wherein the polarization decision module (130; 230) is configured to modify for each input sample of the input samples of the second set of the two or more sets, the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample when the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample is smaller than the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample to obtain a first modified amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample, so that the first modified amplitude value of said first polarization-component sample ($Z_{x,k}$) is smaller than said first amplitude value of said first polarization-component sample ($Z_{x,k}$), and

wherein the polarization decision module (130; 230) is configured to modify for each input sample of the input samples of the second set of the two or more sets, the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample when the first amplitude value of the first polarization-component sample ($Z_{x,k}$) of said input sample is greater than or equal to the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample to obtain a second modified amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, so that the second modified amplitude value of said second polarization-component sample ($Z_{y,k}$) is smaller than said second amplitude value of said second polarization-component sample ($Z_{y,k}$), and

wherein the polarization decision module (130; 230) is configured to not modify the amplitude value of the first polarization-component sample ($Z_{x,k}$) of any of the input samples of a set of the two or more sets, being different from the second set of the two or more sets, and

wherein the polarization decision module (130; 230) is configured to not modify the amplitude value of the second polarization-component sample ($Z_{y,k}$) of any of the input samples of a set of the two or more sets, being different from the second set of the two or more sets.

12. An apparatus according to one of the preceding claims, wherein the receiving interface (110; 210) comprises one or more demultiplexing units (212; 214) for demultiplexing at least some of the samples of the input sequence such that the samples are demultiplexed for parallel processing.

13. An apparatus according to one of the preceding claims,

wherein the determination module (150; 250) comprises an weighting module (252) being configured to determine a plurality of weighted values,

wherein the weighting module (252) is configured to determine each of the plurality of weighted values by multiplying the first polarization-component samples or the second polarization-component samples of at least two of the member samples of the member sample group and a weight, and

wherein the determination module (150; 250) is configured to determine the first phase noise estimate and the second phase noise estimate based at least some of the plurality of weighted values.

14. An apparatus according to one of the preceding claims, wherein the apparatus is configured to determine the first and the second phase noise estimate being phase noise estimates of an optically transmitted signal comprising symbols being modulated by employing a 6-ary polarization-shift keying quadrature phase-shift keying format.

15. An apparatus according to one of the preceding claims, wherein the apparatus is implemented as an application specific integrated circuit.

16. An apparatus for phase correction comprising:

an apparatus (310) according to one of claims 1 to 15 for determining a first and a second phase noise estimate based on one or more input samples, and

a phase correction module (320) for conducting phase correction on the one or more input samples based on the one or more phase noise estimates.

17. A method for determining a first and a second phase noise estimate, comprising:

receiving a plurality of input samples of an input sequence, wherein each input sample of the plurality of input samples comprises a first polarization-component sample ($Z_{x,k}$) indicating a first complex value, and a second polarization-component sample ($Z_{y,k}$) indicating a second complex value, wherein a first amplitude value and a first phase value are assigned to said first polarization-component sample ($Z_{x,k}$), wherein said first amplitude value is the amplitude of said first complex value, wherein said first phase value is the phase of said first complex value, wherein a second amplitude value and a second phase value are assigned to said second polarization-component sample ($Z_{y,k}$), wherein said second amplitude value is the amplitude of said second complex value, and wherein said second phase value is the phase of said second complex value,

classifying the input samples of the input sequence into two or more sets by assigning each input sample of the input sequence to exactly one of the two or more sets depending on the first polarization-component sample ($Z_{x,k}$) of said input sample and depending on the second polarization-component sample ($Z_{y,k}$) of said input sample,

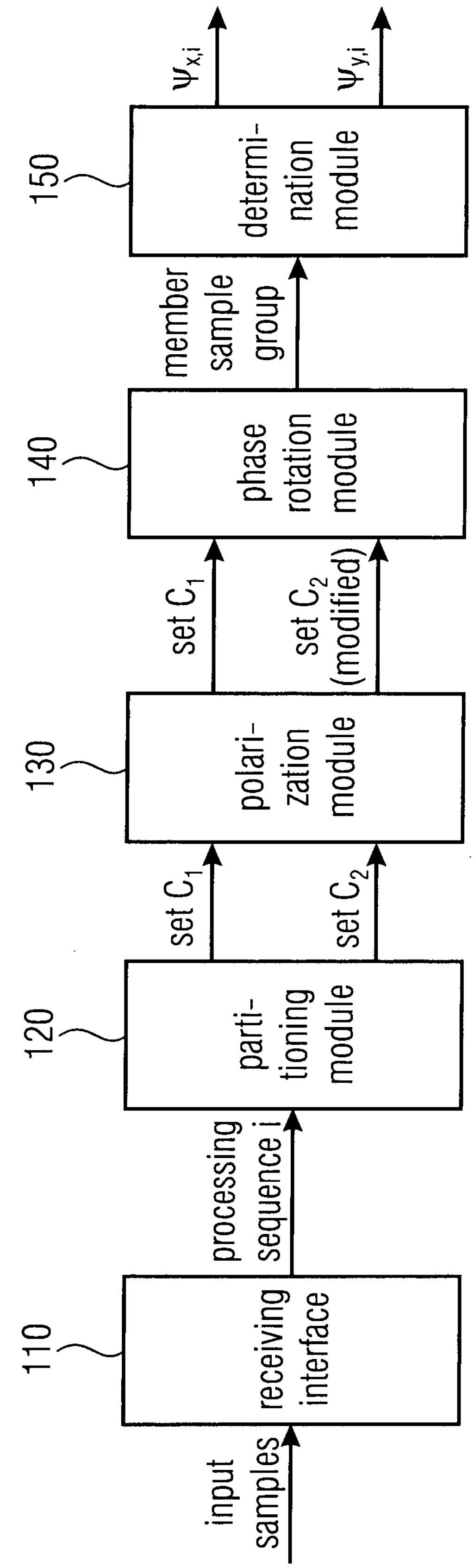
deciding for each input sample of the input samples of a second one of the sets, whether to modify either the first amplitude value of the first polarization-component sample ($Z_{x,k}$) or the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, depending on the first amplitude value of the first polarization-component sample ($Z_{x,k}$) and the second amplitude value of the second polarization-component sample ($Z_{y,k}$) of said input sample, and for modifying either said first amplitude value of said first polarization-component sample ($Z_{x,k}$) or said second amplitude value of said second polarization-component sample ($Z_{y,k}$),

determining a member sample group comprising a plurality of member samples, wherein the step of determining the member sample group comprises determining a plurality of modified samples by modifying each of the input samples of a first set of the two or more sets, being different from the second set of the two or more sets, by applying a phase rotation to the first polarization-component sample and the second polarization-component sample of said input sample to obtain one of the plurality of modified samples, wherein the member sample group is determined so that the member sample group comprises each modified sample of the plurality of modified samples as one of the member samples, wherein the step of determining the member sample group comprises to not modify any of the input samples of the second set of the two or more sets, wherein the member sample group is determined so that the member sample group comprises furthermore each of the input samples of said first set as further one of the member samples,

determining the first phase noise estimate based on the first polarization-component sample ($Z_{x,k}$) of each member sample of the member sample group, and

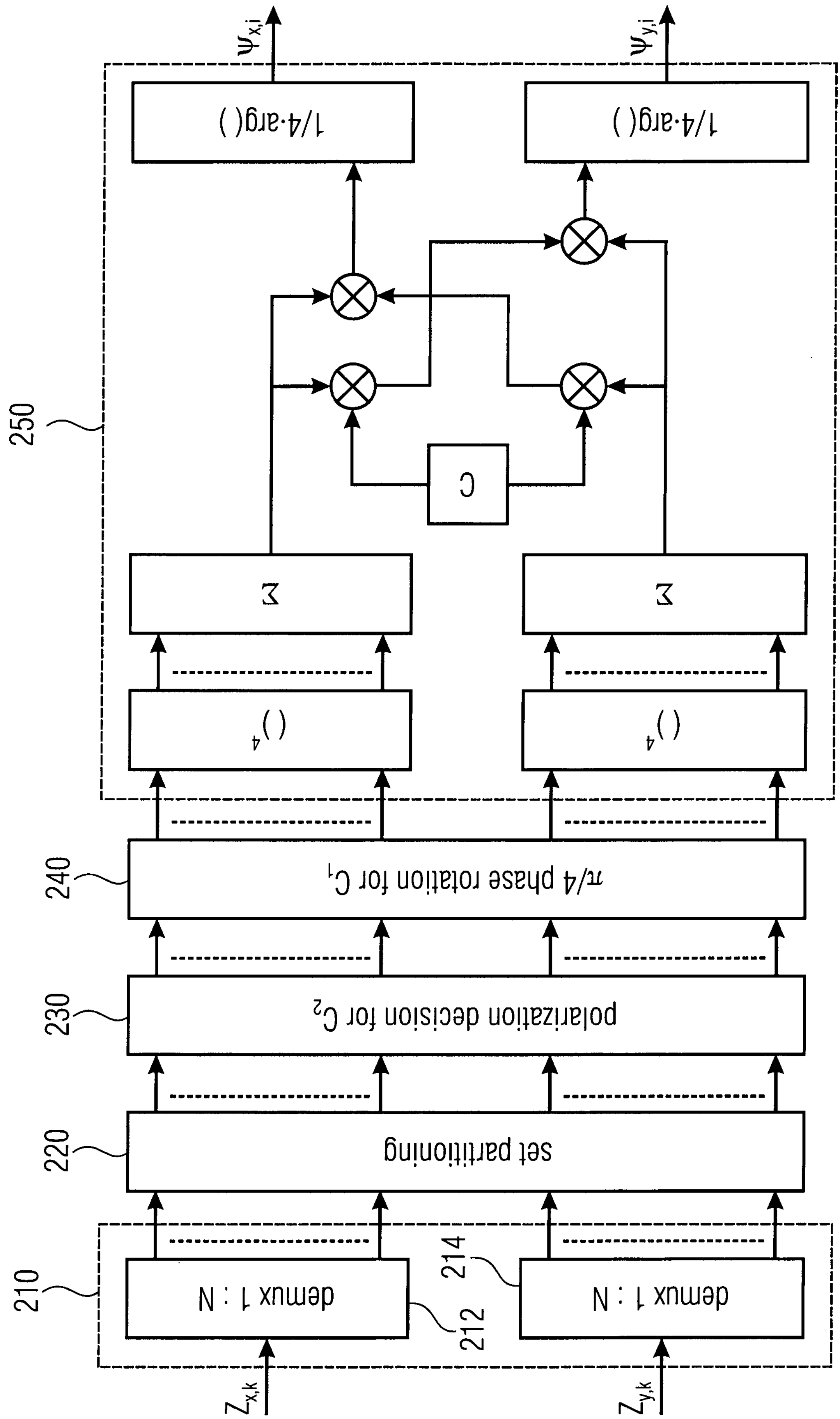
determining the second phase noise estimate based on the second polarization-component sample ($Z_{y,k}$) of each member sample of the member sample group.

18. A computer program for implementing the method of claim 17 when being executed on a computer or signal processor.



input samples
110
receiving interface
processing sequence i
120
parti-tioning module
set $C_1$
set $C_2$
130
polari-zation module
set $C_1$
set $C_2$ (modified)
140
phase rotation module
member sample group
150
determi-nation module
$\psi_{x,i}$
$\psi_{y,i}$


FIG 1



$\Psi_{x,i}$
$\Psi_{y,i}$
1/4·arg( )
1/4·arg( )
250
C
Σ
Σ
( )$^4$
( )$^4$
240
π/4 phase rotation for $C_1$
230
polarization decision for $C_2$
220
set partitioning
210
214
demux 1 : N
demux 1 : N
212
$Z_{x,k}$
$Z_{y,k}$


FIG 2

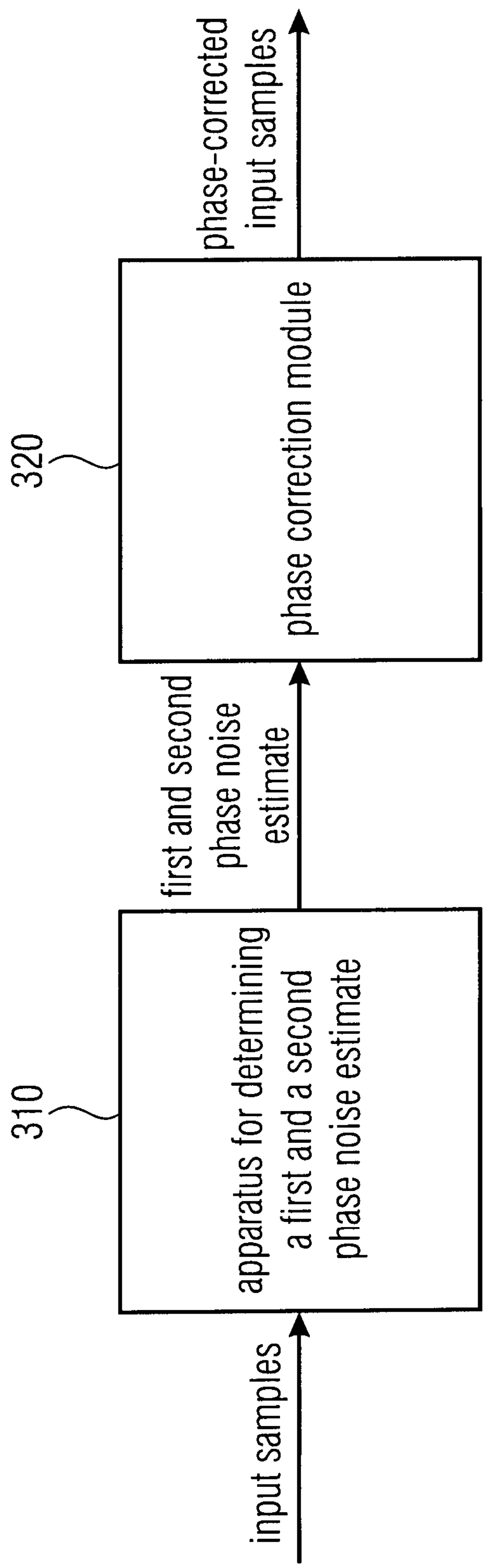
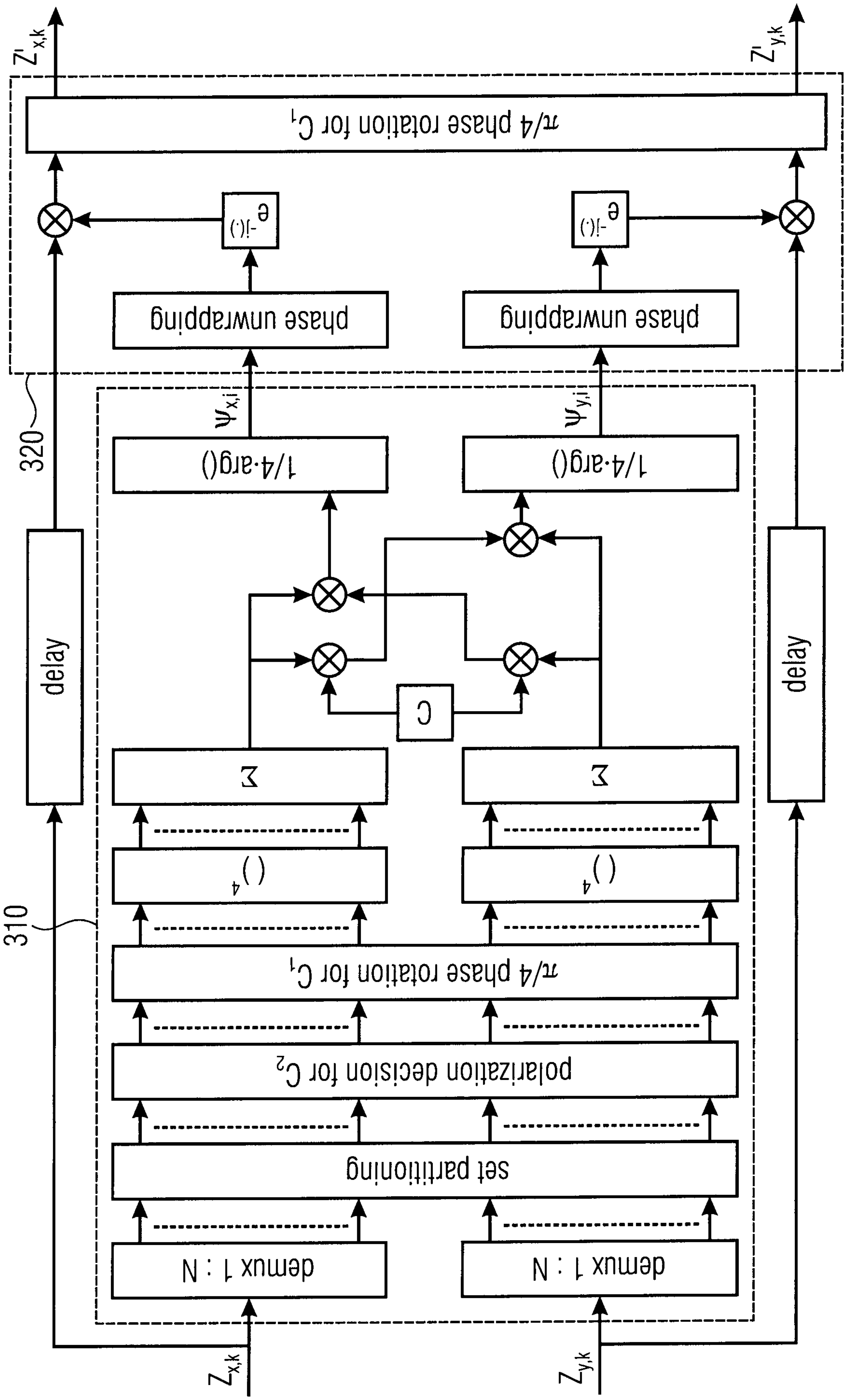

input samples
310
apparatus for determining
a first and a second
phase noise estimate
first and second
phase noise
estimate
320
phase correction module
phase-corrected
input samples

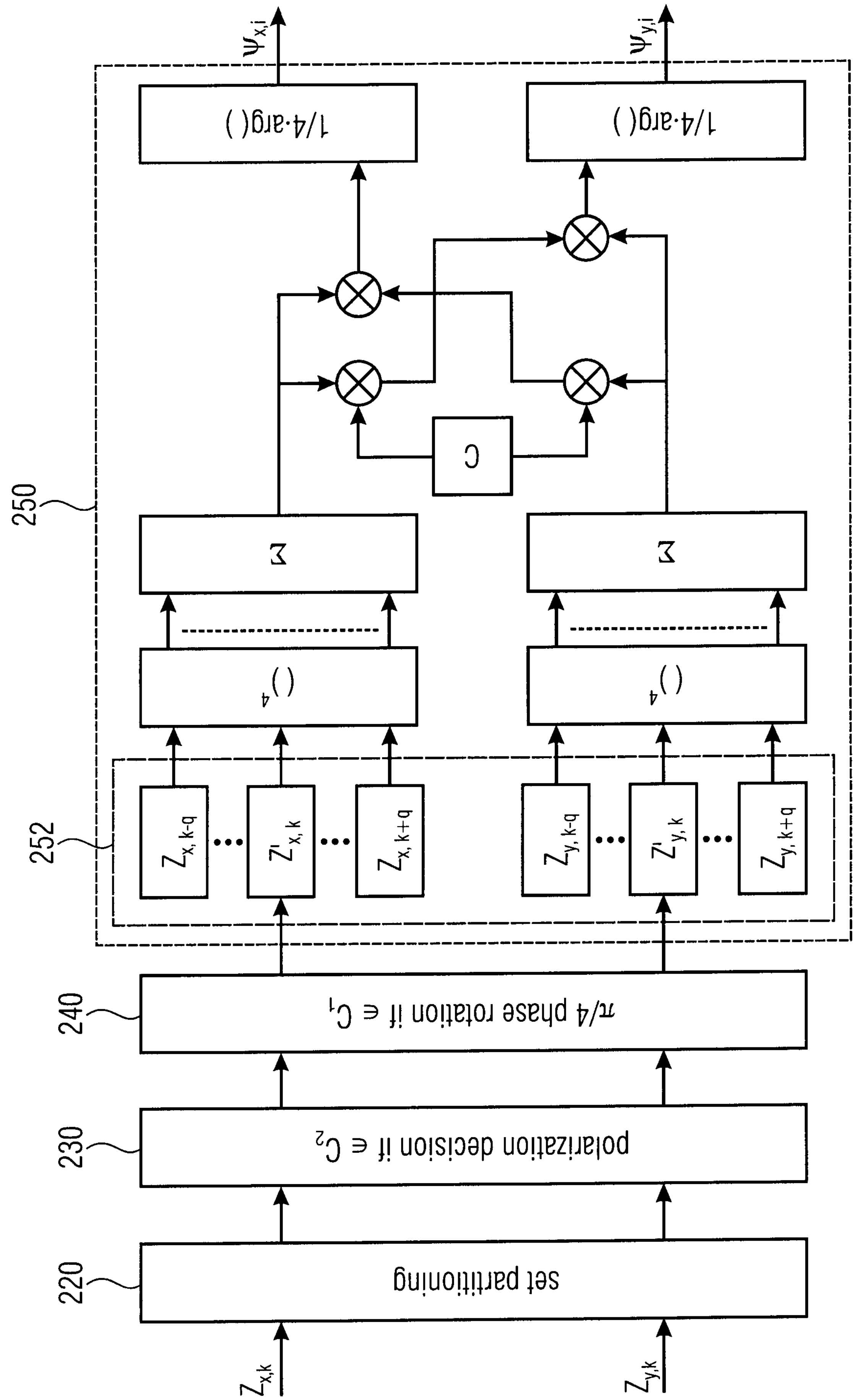
FIG 3



Z'x,k
Z'y,k
π/4 phase rotation for C1
e^-j(·)
phase unwrapping
ψx,i
ψy,i
320
1/4·arg()
delay
C
Σ
( )^4
310
polarization decision for C2
set partitioning
demux 1 : N
Zx,k
Zy,k


FIG 4

5/10



Ψx,i
Ψy,i
1/4·arg( )
1/4·arg( )
C
Σ
Σ
( )4
( )4
250
252
Zx, k-q
Z'x, k
Zx, k+q
Zy, k-q
Z'y, k
Zy, k+q
240
π/4 phase rotation if ∈ C1
230
polarization decision if ∈ C2
220
set partitioning
Zx,k
Zy,k


FIG 5A

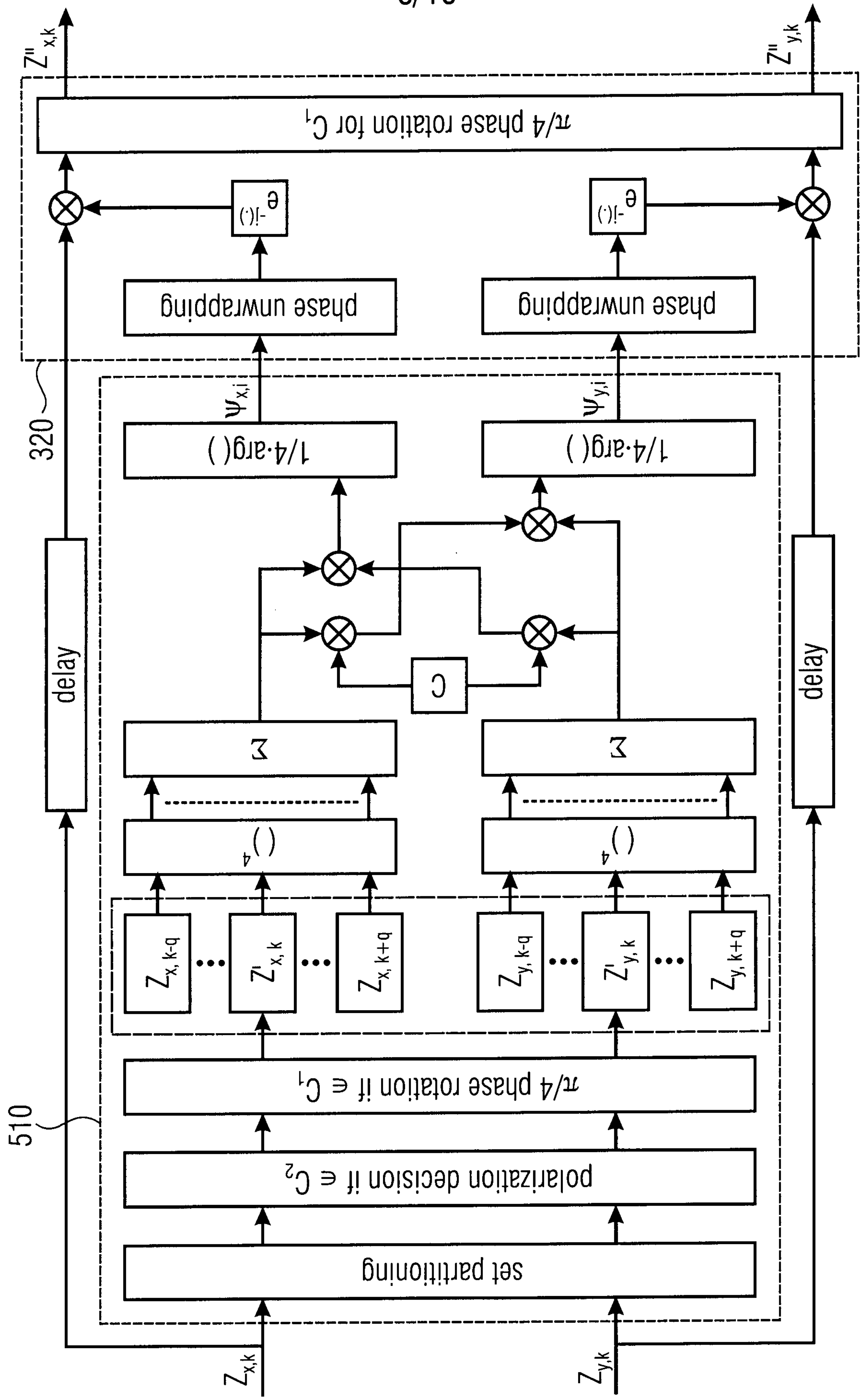

$Z''_{x,k}$
$Z''_{y,k}$
$\pi/4$ phase rotation for $C_1$
$e^{-j(\cdot)}$
$e^{-j(\cdot)}$
phase unwrapping
phase unwrapping
320
$\psi_{x,i}$
$\psi_{y,i}$
1/4·arg( )
1/4·arg( )
delay
delay
C
Σ
Σ
$(\,)^4$
$(\,)^4$
$Z_{x,k-q}$
$Z'_{x,k}$
$Z_{x,k+q}$
$Z_{y,k-q}$
$Z'_{y,k}$
$Z_{y,k+q}$
$\pi/4$ phase rotation if $\in C_1$
510
polarization decision if $\in C_2$
set partitioning
$Z_{x,k}$
$Z_{y,k}$

FIG 5B

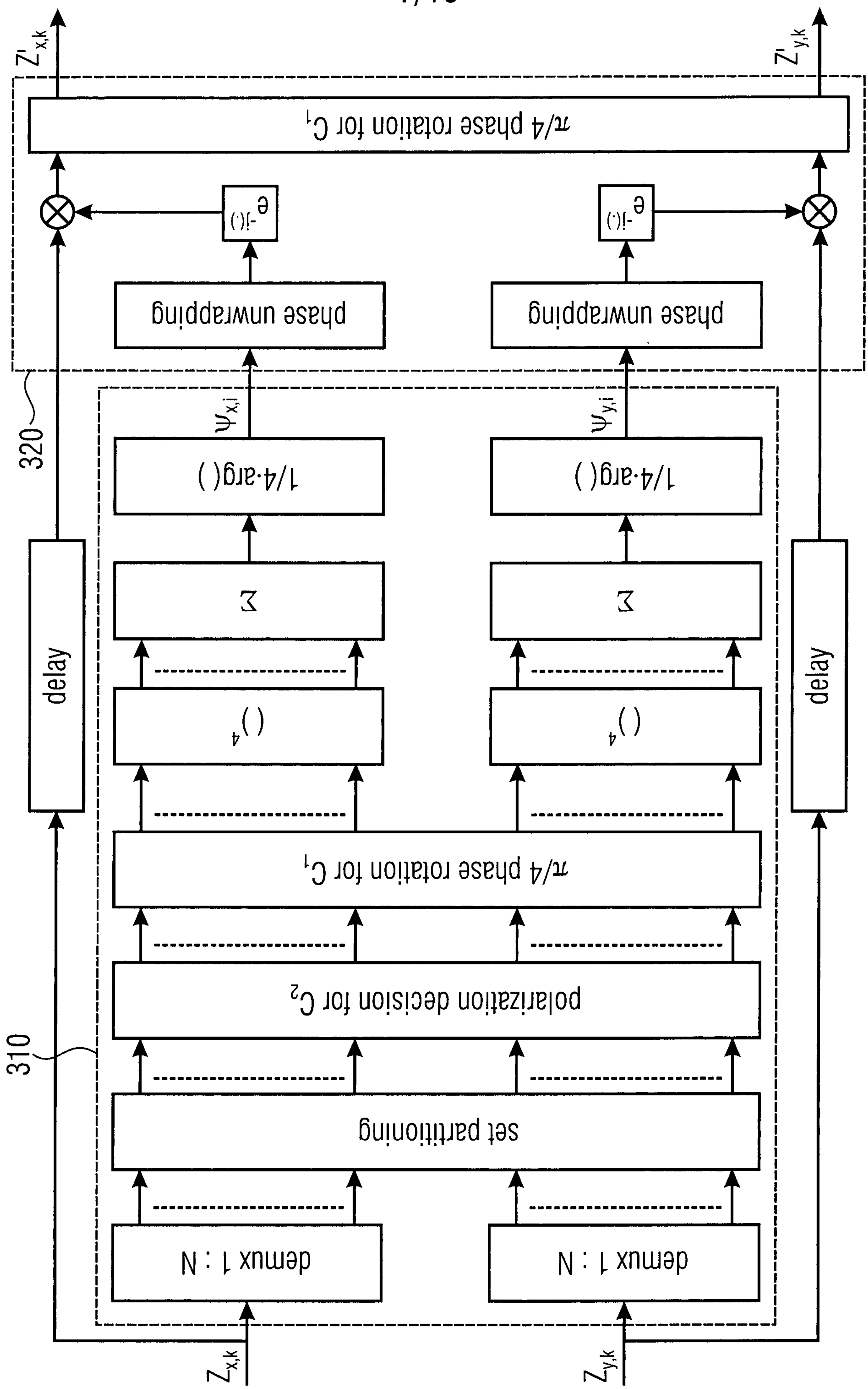

$Z'_{x,k}$
$Z'_{y,k}$
π/4 phase rotation for $C_1$
$e^{-j(\cdot)}$
$e^{-j(\cdot)}$
phase unwrapping
phase unwrapping
320
$\Psi_{x,i}$
$\Psi_{y,i}$
1/4·arg( )
1/4·arg( )
Σ
Σ
delay
delay
$(\,)^4$
$(\,)^4$
π/4 phase rotation for $C_1$
polarization decision for $C_2$
310
set partitioning
demux 1 : N
demux 1 : N
$Z_{x,k}$
$Z_{y,k}$

FIG 6

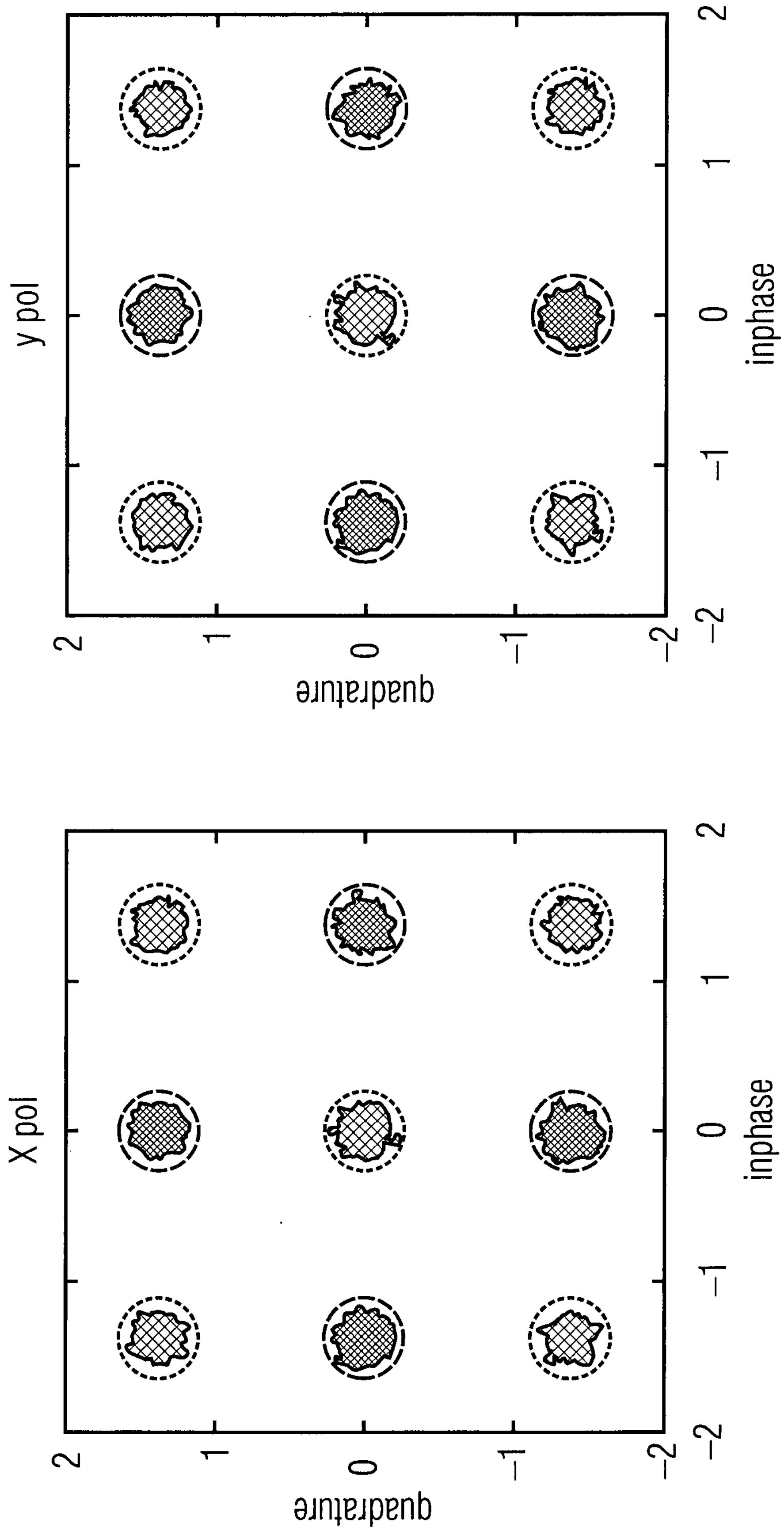

y pol
quadrature
inphase
2
1
0
−1
−2
X pol
quadrature
inphase
2
1
0
−1
−2

FIG 7A

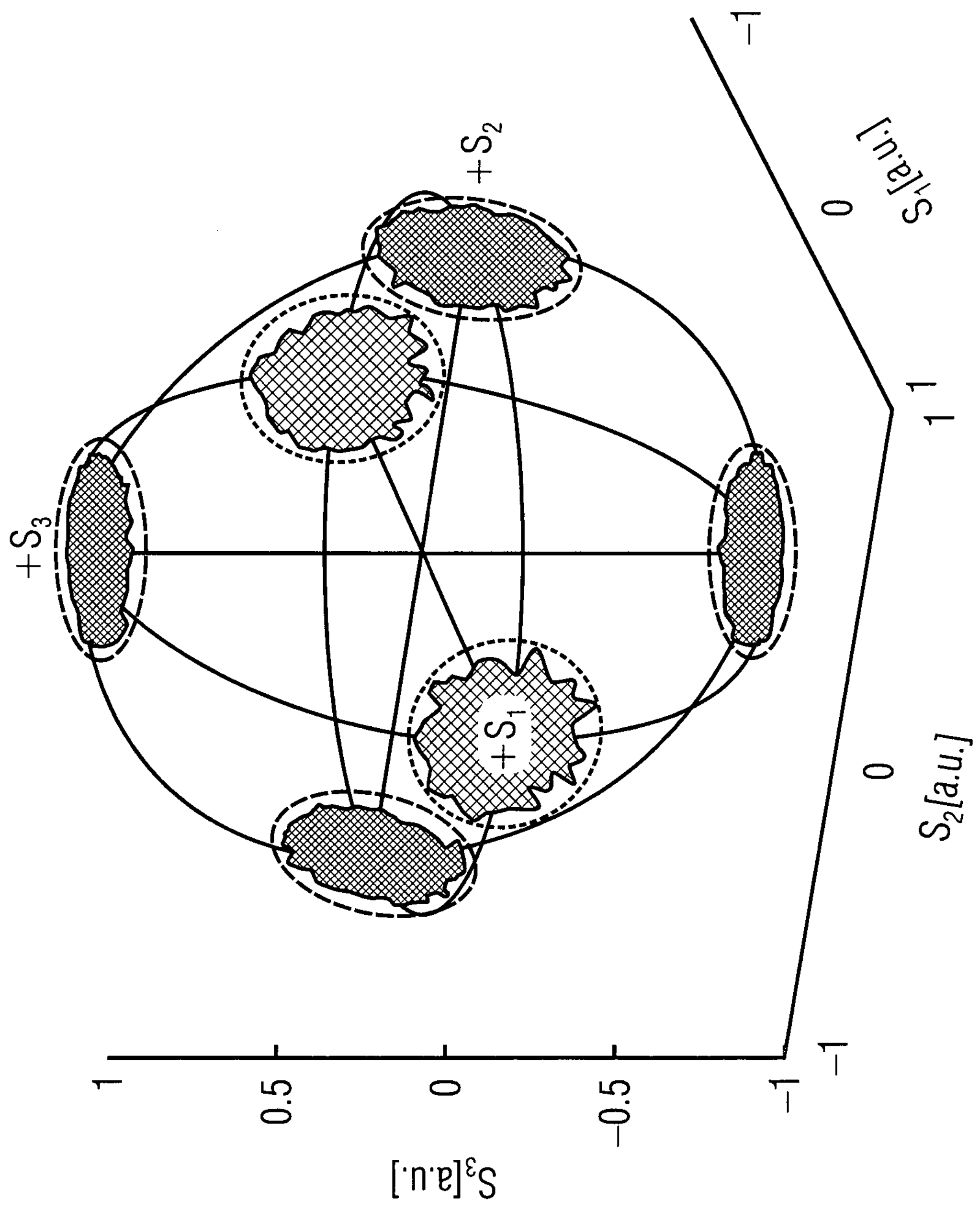



FIG 7B

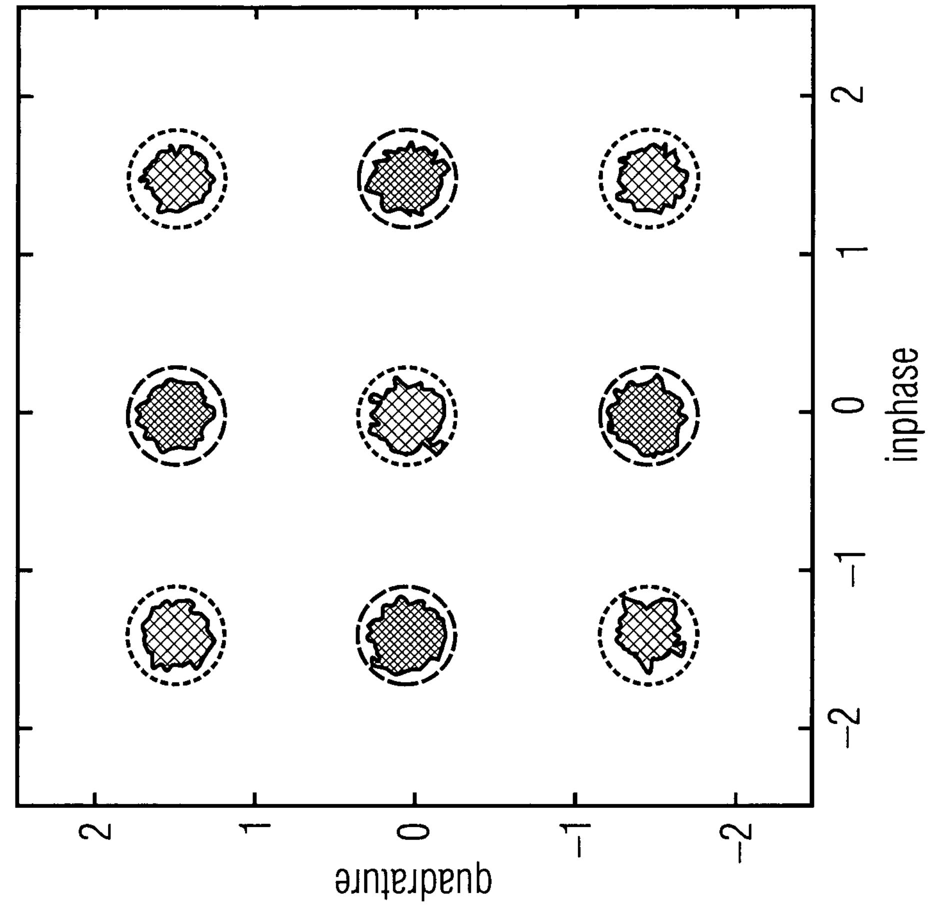



FIG 8B

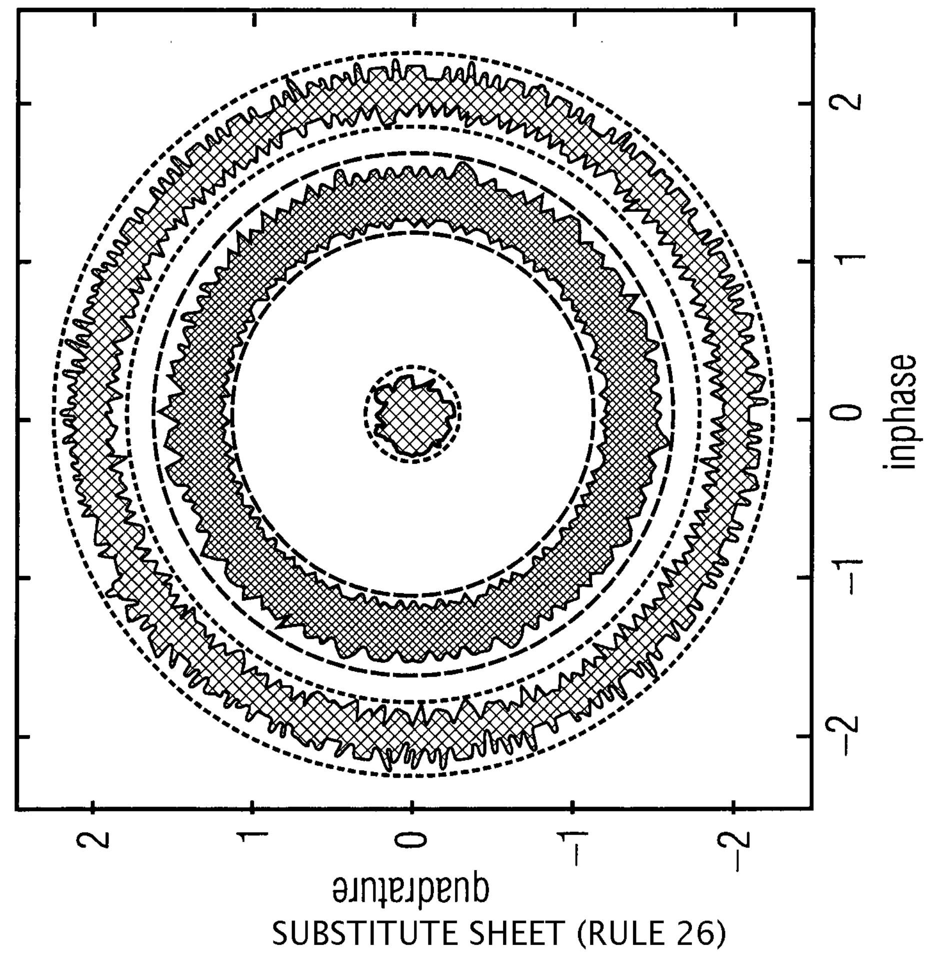



FIG 8A

# INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/050848

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/61 H04B10/532
ADD.

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)
H04B

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)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | SALEEM ALREESH ET AL: "Joint-Polarization Carrier Phase Estimation for PS-QPSK Signals", IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 24, no. 15, 1 August 2012 (2012-08-01), pages 1282-1284, XP011448292, ISSN: 1041-1135, DOI: 10.1109/LPT.2012.2201933 abstract paragraph [00II] ----- | 1-18 |
| | -/-- | |

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

* Special categories of cited documents :

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"E" earlier application or patent but 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 | Date of mailing of the international search report |
|---|---|
| 10 October 2013 | 21/10/2013 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016 | Douglas, Ian |

1

| C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT | | |
|---|---|---|
| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| A | FISCHER, ALREESH ET AL.: "Experimental Investigation of 126-Gb/s 6PolSK-QPSK signals", OPTICS EXPRESS, vol. 20, no. 26, 29 December 2012 (2012-12-29), XP002714393, paragraph [0002] ----- | 1-18 |

1