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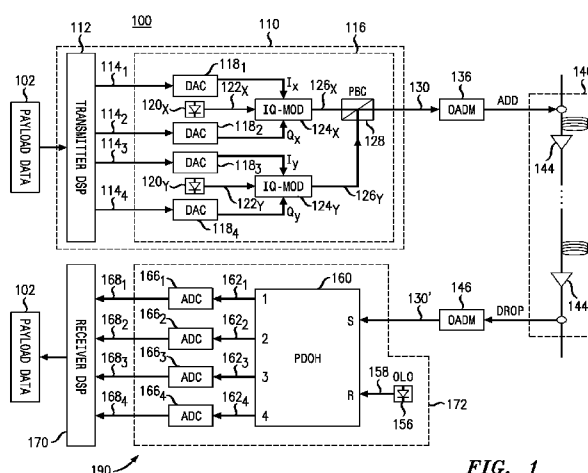


FIG. 1

(57) Abstract: An apparatus comprises an optical transmitter that comprises a processor and at least one optical modulator. The processor is configured to generate electronic representations of at least two pre-dispersion-compensated phase-conjugated optical variants carrying a same modulated payload data for transmission. The at least one optical modulator is configured to modulate the electronic representations, wherein an amount of dispersion induced on the pre-dispersion-compensated phase-conjugated optical variants depends on an accumulated dispersion (AD) of a transmission link through which the pre-dispersion-compensated phase-conjugated optical variants are to be transmitted. The amount of dispersion induced on the phase-conjugated optical variants may be approximately $-AD/2$, where AD is the accumulated dispersion of the transmission link. The pre-dispersion-compensated phase-conjugated optical variants are different from one another in one or more dimensions such as the polarization of light, the time of transmission, the spatial localization, the optical carrier wavelength, or the subcarrier frequency during transmission.

COMMUNICATION THROUGH PRE-DISPERSION-COMPENSATED PHASE- CONJUGATED OPTICAL VARIANTS

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application claims priority from U.S. Provisional Patent Application No. 61/535,548, filed on September 16, 2011, and U.S. Patent Application No. 13/245160, filed on September 26, 2011, both entitled "PERFORMANCE ENHANCEMENT THROUGH OPTICAL VARIANTS," which are incorporated herein by reference in its entirety. This application also claims priority from U.S. Patent Application No. 10 13/411462, filed on March 2, 2012, entitled "COMMUNICATION THROUGH PHASE-CONJUGATED OPTICAL VARIANTS," which is incorporated herein by reference in its entirety

BACKGROUND

15 Field

The invention(s) relate to optical communication equipment and, more specifically but not exclusively, to equipment for managing data transport through a nonlinear and/or noisy optical channel.

20 Description of the Related Art

This section introduces aspects that may help facilitate a better understanding of the invention(s). Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is in the prior art or what is not in the prior art.

25 Forward error correction (FEC) uses systematically generated redundant data to reduce the bit-error rate (BER) at the receiver. The cost of this reduction is a concomitant increase in the required forward-channel bandwidth, the latter being dependent on the overhead of the FEC code. In general, an FEC code with a larger overhead or lower net data rate is used for a noisier channel. When the channel 30 conditions change over time, the net data rate and/or the FEC code can be adaptively

changed to maintain an acceptable BER. However, one problem with FEC coding, as applied to optical transmission systems, is that the coding-gain differences among various implementable FEC codes usually do not exceed a certain maximum value, as given by Shannon's information capacity theory. In addition, the digital signal processing (DSP) complexity for capacity-approaching FEC codes can be forbiddingly high. Therefore, for certain optical channels, additional and/or alternative performance-enhancement techniques may be needed to overcome these and other pertinent limitations of FEC coding.

10

SUMMARY

Improvement in the quality of an optical signal after transmission may be obtained by performing digital constructive summation of a set of two or more optical variants. Optical variants are correlated optical signals which carry the same piece of payload data, bit-word, or bit sequence but differ from each other in at least one of their degrees of freedom, e.g., in one or more of the time of transmission, spatial localization, polarization of light, optical carrier wavelength and subcarrier frequency. The constructive summation tends to average out, to a certain degree, the deleterious effects of both linear and nonlinear noise/distortions imparted on the individual optical variants in the optical transmission link because said noise/distortions are incoherent in nature. The optical variants can be the same as the original optical signal intended for transmission, or phase-scrambled copies of original signal.

Nonlinear distortions imparted on two phase-conjugated signals during transmission can be essentially opposite to each other when the phase conjugation is removed at the receiver. Therefore, when two phase-conjugated optical variants carrying the same modulated payload symbols are coherently summed after removing the phase conjugation between them, the nonlinear distortions imparted on the two phase-conjugated optical variants would essentially cancel. It is further found that in highly dispersive transmission, application of a symmetric dispersion map may be additionally utilized in order to achieve effective cancellation of the nonlinear distortions imparted on the two phase-conjugated optical variants. The symmetric dispersion map can be

realized by pre-compensating the phase-conjugated optical variants by an amount of dispersion that depends on the accumulated dispersion (e.g., power-weighted accumulated dispersion (AD_{PW})) of a transmission link, through which the optical variants are to be transmitted. This methodology effectively improves signal quality after
5 nonlinear dispersive transmission, beyond what can be achieved by coherently summing two optical variants that are either duplicated or phase-scrambled copies of a same optical signal.

In one embodiment, an apparatus comprises an optical transmitter, which comprises a processor configured to generate electronic representations of at least two
10 pre-dispersion-compensated phase-conjugated optical variants carrying a same modulated payload data for transmission; and at least one optical modulator for modulating the electronic representations, wherein an amount of dispersion induced on the pre-dispersion-compensated phase-conjugated optical variants depends on an accumulated dispersion (AD) of a transmission link through which the pre-dispersion-
15 compensated phase-conjugated optical variants are to be transmitted. The processor may be configured to generate the electronic representations by convolving an E-field representation with a pre-dispersion-compensation function.

In one embodiment, the amount of dispersion induced on the phase-conjugated optical variants through the pre-dispersion-compensation is approximately $-AD_{PW}/2$,
20 where AD_{PW} is the power-weighted accumulated dispersion of the transmission link. In another embodiment, the amount of dispersion induced on the phase-conjugated optical variants through the pre-dispersion-compensation is approximately negative one-half of the accumulated dispersion of the transmission link. The accumulated dispersion of the transmission link may be power weighted to account for the launch power into the
25 various spans comprising the transmission link, since the launch power may not be uniform for each span of the transmission link.

In one embodiment, the at least two pre-dispersion-compensated phase-conjugated optical variants, upon exiting the transmitter, differ from one another in one or more of polarization, time of transmission, spatial localization, optical carrier
30 wavelength, and subcarrier frequency. The digital representations of the at least two pre-

dispersion-compensated phase-conjugated optical variants may be complex conjugates before being pre-dispersion compensated. In one embodiment, one digital representation of the at least two pre-dispersion-compensated phase-conjugated optical variants includes a complex conjugate version of the payload data for transmission with a constant phase
5 rotation before being pre-dispersion compensated.

In one embodiment, the transmitter comprises two optical modulators configured to generate two orthogonally-polarized pre-dispersion-compensated phase-conjugated optical variants at a same wavelength. The same modulated payload data for transmission may use a modulation scheme selected from the group consisting of
10 amplitude-shift keyed (ASK), phase-shift keyed (PSK), quadrature-amplitude modulated (QAM), or polarization-division-multiplexed (PDM) signals, or a combination thereof.

In one embodiment, the apparatus also includes a transmission link, which includes an optical pre-dispersion compensation module, an optical in-line dispersion compensation module, an optical post-dispersion compensation module, or a combination
15 thereof. In one embodiment, the apparatus also includes a transmission link, which may be one or more of single-mode fiber, fiber bundle, multi-core-fiber, and multi-mode fiber. In another embodiment, the apparatus also includes a transmission link which includes an optically amplified transmission fiber span.

In one embodiment, the apparatus also includes an optical receiver for receiving
20 versions of at least two pre-dispersion-compensated phase-conjugated optical variants. The optical receiver may comprises a front-end circuit configured to convert the received versions of at least two pre-dispersion-compensated phase-conjugated optical variants carrying same modulated payload data into a corresponding plurality of digital electrical signals; and a processor configured to: process the plurality of digital electrical signals to
25 generate a set of complex values representing the same modulated payload data, sum the complex values of the set to generate a summed complex value, map the summed complex value onto a constellation, and determine based on the mapped summed complex value a data represented by the same modulated payload data.

30 In one embodiment, the processor configured to process the plurality of digital

electrical signals to generate a set of complex values representing the same modulated payload data is configured to perform post-dispersion compensation on the received versions of at least two pre-dispersion-compensated phase-conjugated optical variants; and remove phase conjugation between the received versions of the at least two pre-
5 dispersion-compensated phase-conjugated optical variants.

In one embodiment, the optical receiver comprises at least one polarization-diversity optical hybrid, one optical local oscillator, and four analog-to-digital convertors (ADCs).

In one embodiment, the processor configured to generate a set of complex values
10 representing the same modulated payload symbol is configured to compensate for residual dispersion of the received versions of at least two pre-dispersion-compensated phase-conjugated optical variants. In another embodiment, the processor configured to process the plurality of digital electrical signals to generate the set of complex values representing the same modulated payload symbol is configured to perform one or more of
15 time synchronization, channel estimation, channel compensation, frequency estimation, frequency compensation, phase estimation, and phase compensation.

In one embodiment, the apparatus also include a transmission link; and at least one phase-sensitive optical amplifier for amplifying at least two pre-dispersion-compensated phase-conjugated optical variants in the transmission link. The phase-
20 sensitive optical amplifier is an optical parametric amplifier.

In one embodiment, the transmitter is configured to transmitted the pre-dispersion-compensated phase-conjugated optical variants on different paths for a same receiver and with a signal quality such that the payload data cannot be decoded with detection of a single pre-dispersion compensated phase-conjugated optical variant, the
25 method thereby providing security of communication between the transmitter and a receiver.

According to one embodiment, the pre-dispersion-compensation is realized by digital signal processing modules that digitally pre-compensate the complex fields representing the phase-conjugated optical variants. In an embodiment, digital signal
30 processing modules that digitally pre-compensate the complex fields representing the

phase-conjugated optical variants utilize the overlap-and-add method.

According to another embodiment, pre-dispersion-compensation is realized by an optical dispersion compensation module (DCM) that optically pre-compensates the complex fields representing the phase-conjugated optical variants.

5 In another embodiment, the at least two pre-dispersion-compensated phase-conjugated optical variants can differ from one another in one or more of polarization, time, spatial localization, optical carrier wavelength, and subcarrier frequency during optical transmission. Two “phase-conjugated optical variants” refer to two optical variants that are complex conjugates after removing a constant phase offset and/or time
10 delay between them. Further, more than two phase-conjugated optical variants may be utilized in the provided methodology; in those instances, the third, fourth, etc. phase-conjugated optical variant is a copy of one of first two complex conjugates after removing a constant phase offset and/or time delay from the third, fourth, etc. phase-conjugated optical variant.

15 According to one embodiment, at least two pre-dispersion-compensated phase-conjugated optical variants are orthogonally polarized, and are generated by a polarization-diversity transmitter and share the same wavelength and spatial path in an optical fiber transmission link. A polarization-diversity receiver is used to receive the at least two orthogonal polarization components and jointly process them to recover the
20 transmitted optical variants. The recovery process includes post-dispersion-compensation to bring the overall dispersion experienced by the signals to approximately zero (e.g., essentially zero). Then, the phase conjugation between these two variants is removed, before the variants are constructively summed to provide a constellation representation of the original signal.

25 According to one embodiment, at least two pre-dispersion-compensated phase-conjugated optical variants for an optical signal intended for transmission are time delayed with respect to each other by τ , which may be multiple modulation symbol periods, and modulated onto a polarization component of a Polarization Division Multiplexed (PDM) signal. At the receiver, the time delay and the phase conjugation

between these two variants are removed, before their constructive summation to provide a constellation representation of the original signal.

According to one embodiment, at least two pre-dispersion-compensated phase-conjugated optical variants are modulated onto different optical carrier wavelengths, and are wavelength-division multiplexed for transmission. Each of the optical variants can be a polarization-division-multiplexed (PDM) signal. These wavelengths can travel through the same spatial path in an optical fiber transmission link. At the receiver, these optical variants are first wavelength-division de-multiplexed and jointly processed. Then, the phase conjugation between these variants is removed before they are constructively summed to provide a constellation representation of the original signal.

According to one embodiment, at least two pre-dispersion-compensated phase-conjugated optical variants are space-division multiplexed for transmission. These at least two optical variants can travel through different fiber paths, different cores of a multicore fiber link, different spatial modes of a multi-mode fiber, or different transmission paths as long as the nonlinear effects impacting them are approximately the same. At the receiver, these at least two optical variants are first space-division de-multiplexed, either optically or digitally, and jointly processed. Then, the phase conjugation between these at least two variants is removed, after which they are constructively summed to provide a constellation representation of the original signal.

As the linear noises impacting each of the optical variants are uncorrelated, the constructive summation process aforementioned also effectively increases the optical signal-to-noise (OSNR). Together with the cancellation of nonlinear distortions, the use of pre-dispersion-compensated phase-conjugated optical variants in a constructive summation process can substantially improve the signal quality in long-haul optical fiber transmission, regardless of the dispersion present in the transmission fiber.

In various embodiments, the signal quality improvement or the reduction in the received bit error ratio (BER) enabled by the use of optical variants can be implemented in addition to or instead of that provided by FEC coding.

In an embodiment, a method comprises generating, by a processor, digital representations of at least two pre-dispersion-compensated phase-conjugated optical

variants carrying a same modulated payload data for transmission; and modulating, by at least one optical modulator, the digital representations, wherein an amount of dispersion induced on the pre-dispersion compensated phase-conjugated optical variants depends on an accumulated dispersion (AD) of a transmission link through which the pre-dispersion compensated phase-conjugated optical variants are to be transmitted. Generating the digital representations may include convolving an E-field representation with a pre-dispersion-compensation function. The amount of dispersion induced on the pre-dispersion-compensated phase-conjugated optical variants may be about $-AD/2$, where AD is the accumulated dispersion of the transmission link through which the phase-conjugated optical variants are to be transmitted. The accumulated dispersion may be a power-weighted accumulated dispersion of the transmission link through which the phase-conjugated optical variants are to be transmitted.

In one embodiment, generating the digital representations includes inducing dispersion by electronically pre-compensating complex fields representing phase-conjugated optical variants. In one embodiment, the pre-dispersion-compensated phase-conjugated optical variants are transmitted through different paths for a same receiver and with a signal quality such that the payload data cannot be decoded with detection of a single pre-dispersion compensated phase-conjugated optical variant, the method thereby providing security of communication between the transmitter and a receiver. The method may also include converting, at an optical receiver, received versions of at least two pre-dispersion-compensated phase-conjugated optical variants carrying same modulated payload data into a corresponding plurality of digital electrical signals; processing the plurality of digital electrical signals to generate a set of complex values representing the same modulated payload data; summing the complex values of the set to generate a summed complex value; mapping the summed complex value onto a constellation; and determining based on the mapped summed complex value a data represented by the same modulated payload data.

In yet another embodiment, an apparatus includes an optical transmitter comprising a processor configured to generate electronic representations of at least two phase-conjugated optical variants carrying a same modulated payload data for

transmission; at least one optical modulator for modulating the electronic representations; and an optical dispersion compensator configured to provide pre-dispersion compensation of the modulated electronic representations, wherein the amount of dispersion compensated depends on an accumulated dispersion (AD) of a transmission link through which the modulated electronic representations are to be transmitted.

In an embodiment, the at least two pre-dispersion-compensated phase-conjugated optical variants are complex conjugates before the pre-dispersion compensation.

In an embodiment, the at least two pre-dispersion-compensated phase-conjugated optical variants include a complex conjugate version of the optical version of the symbol for transmission with a constant phase rotation before the pre-dispersion compensation.

In an embodiment, two optical modulators generate two orthogonally-polarized pre-dispersion-compensated phase-conjugated optical variants at a same wavelength.

In an embodiment, the processor of the receiver is further configured to compensate for the residual dispersion of the at least two phase-conjugated optical variants.

In one embodiment, the processor may determine the bit-word represented by the same modulated payload symbol by determining a FEC-based error correction based on a sequence of mapped constellations for a sequence of same modulated payload symbols. In another embodiment, processing the plurality of digital electrical signals to generate the set of complex values representing the same modulated payload symbol may include performing one or more of time synchronization, channel estimation, channel compensation, frequency estimation, frequency compensation, phase estimation, and phase compensation. This processing of the digital electrical signals may include the use of pilot symbols.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of various embodiments of the invention will become more fully apparent, by way of example, from the following detailed description and the accompanying drawings, in which:

FIG. 1 shows a block diagram of an optical transmission system according to one embodiment of the invention;

FIG. 2 shows a flowchart of a signal-processing method that can be implemented in the transmitter of the optical transmission system shown in FIG. 1 according to one
5 embodiment of the invention;

FIG. 3 shows a flowchart of a signal-processing method that can be implemented in the receiver of the optical transmission system shown in FIG. 1 according to one embodiment of the invention;

FIG. 4 shows a block diagram of an optical transmission system according to
10 another embodiment of the invention;

FIG. 5 shows a block diagram of an optical transmission system according to yet another embodiment of the invention;

FIG. 6 shows a flowchart of a signal-processing method that can be implemented in the transmitter of the optical transmission system shown in FIG. 4 and FIG. 5
15 according to one embodiment of the invention; and

FIG. 7 shows a flowchart of a signal-processing method that can be implemented in the receiver of the optical transmission system shown in FIG. 4 and FIG. 5 according to one embodiment of the invention;

20

DETAILED DESCRIPTION

Typical optical transmission links are able to support multiple degrees of freedom, such as time, space, carrier frequency (wavelength), and polarization. Each of these degrees of freedom can be used for optical-signal multiplexing. Multiplexing techniques corresponding to these four different individual degrees of freedom are referred to in the
25 literature as time-division multiplexing, space-division multiplexing, wavelength-division multiplexing, and polarization-division multiplexing.

In addition to or instead of using the various degrees of freedom supported by an optical transmission link for multiplexed transmission of independent optical signals, various embodiments of the invention employ these degrees of freedom for the
30 transmission of correlated optical signals, referred to as optical variants. In a

representative embodiment, two optical variants are two optical signals that carry the same piece of payload data, bit-word, or bit sequence, but differ from each other in the way they carry the payload data: in a representative embodiment, these two optical variants are complex conjugates. Assuming that the E-field of an optical signal intended for transmission is E, the E-field of one of the two optical variants can be E, and the other can be E*, where "*" denotes complex conjugate.

Here, introduced is a more general term "phase-conjugated optical variants", which refers to two optical variants that are complex conjugates after removing a constant phase offset and/or time delay between them. By complex conjugates is meant a pair of complex numbers, both having the same real part, but with imaginary parts of equal magnitude and opposite signs. For example, E₁(t) and E₂(t) are phase-conjugated optical variants of an optical signal intended for transmission E(t) when the following conditions are satisfied

$$\begin{aligned} E_1(t-t_1) &= \exp(j\phi_1) \cdot E(t), \\ E_2(t-t_2) &= \exp(j\phi_2) \cdot E(t)^*, \end{aligned} \quad (1)$$

where j denotes the imaginary unit, t denotes time, t₁ and t₂ are time offsets, and ϕ_1 and ϕ_2 are phase offsets. From the above equations, we have

$$E_1(t-t_1) = \exp[j(\phi_1 + \phi_2)] \cdot E_2(t-t_2)^*, \quad (2)$$

i.e., E₁(t) and E₂(t) are complex conjugates after removing a constant phase offset of ($\phi_1 + \phi_2$) and a time delay of ($t_1 - t_2$). When there are more than two phase-conjugated optical variants, the additional phase-conjugated optical variants take the form:

$$\begin{aligned} E_n(t-t_n) &= \exp[j\phi_n(t)] \cdot E(t), \text{ or} \\ E_n(t-t_n) &= \exp[j\phi_n(t)] \cdot E(t)^*, \end{aligned} \quad (3)$$

where n is 3, 4, ..., and $\phi_n(t)$ can be a known phase sequence, e.g., a phase sequence that can be used for scrambling the phases of the optical variants.

Each of the optical variants can be further extended to be a vector signal, or a polarization-division-multiplexed (PDM) signal. In this case, the original signal E(t) can be in the form of a 2x1 vector

$$E(t) = \begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix}. \quad (4)$$

To generate “pre-dispersion-compensated” phase-conjugated optical variants, the E-fields of the original signal variants, $E_{n, \text{Pre}}(t)$, are effectively convolved with a pre-dispersion-compensation function $H_{\text{Pre}}(t)$ as follows

$$E_{n, \text{Pre}}(t) = H_{\text{Pre}}(t) \otimes E_n(t) \quad (5)$$

where ‘ $\otimes$ ’ denotes convolution as defined :

$$H(t) \otimes E(t) = \int_{-\infty}^{\infty} H(\tau) E(t - \tau) d\tau. \quad (6)$$

A convolution is the integral of the product of two functions after one is reversed and shifted producing a third function that is typically viewed as a modified version of one of the original functions, giving the area overlap between the two functions as a function of the amount that one of the original functions is translated. The above convolution operation can be simply realized in the frequency domain as

$$H(t) \otimes E(t) = F^{-1} \{ F[H(t)] \cdot F[E(t)] \}, \quad (7)$$

where $F(x)$ is the Fourier transform of function x . The size of the discrete Fourier transform (DFT) and inverse DFT (IDFT) used to covert time-domain signal E-field to the frequency domain and back can vary between being at least the same size as the dispersion-induced channel memory length to 10 times such length, the size being chosen to balance processing latency and hardware requirements with acceptable accuracy. The size of the DFT and IDFT used to covert time-domain signal E-field to the frequency domain and back is usually a few times the dispersion-induced channel memory length. The frequency-domain dispersion compensation can be realized by using the overlap-and-add approach. A more detailed description on the overlap-and-add approach can be found in a paper entitled “Coherent optical single carrier transmission using overlap frequency domain equalization for long-haul optical systems,” published in J. Lightwave Technol., 27, 3721- 3728 (2009) by R. Kudo, T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano, and Y. Miyamoto, which is incorporated herein by reference in its entirety.

The amount of dispersion induced on the phase-conjugated optical variants

depends on the accumulated dispersion of a transmission link through which the phase-conjugated optical variants are to be transmitted. In one embodiment, the amount of dispersion induced on the phase-conjugated optical variants depends on the power-weighted accumulated dispersion (AD_{PW}) of a transmission link through which the phase-conjugated optical variants are to be transmitted. Power weighting of the accumulated dispersion of the transmission link accounts for the potential varying of launch power into the various spans comprising the transmission link, since the launch power may not be uniform for each span of the transmission link.

As an example, the power-weighted accumulated dispersion of a transmission link comprising multiple optically amplified homogenous fiber spans is defined as:

$$AD_{PW} = \frac{1}{L_{eff}} \int_0^L e^{G(z)} C(z) dz, \quad (8)$$

where L is the link distance, and $C(z)$ is accumulated dispersion at distance z along the transmission link

$$C(z) = \int_0^z \beta_2(z') dz', \quad (9)$$

where $\beta_2(z')$ is the group-velocity dispersion coefficient at distance z' along the link.

In the above equation, $G(z)$ is the logarithmic loss/gain evolution of the optical signal

$$G(z) = \int_0^z [g(z') - \alpha(z')] dz', \quad (10)$$

where $g(z')$ and $\alpha(z')$ are the gain and loss coefficients at distance z' along the transmission link, respectively, and L_{eff} is the effective length of the transmission link

$$L_{eff} = \int_0^L e^{G(z)} dz. \quad (11)$$

When the amount of dispersion induced on the phase-conjugated optical variants through the pre-dispersion-compensation is approximately $-AD_{PW}/2$ (or the dispersion map is made symmetric about zero dispersion (i.e., pre-dispersion compensation applied such that half way through the transmission link, the accumulated dispersion is zero), we

have

$$C(z) = -C(L - z), \quad (12)$$

and

$$G(z) \approx G(L - z). \quad (13)$$

5 The dimensionless nonlinear transfer function, defined as

$$\eta(\xi) = \frac{1}{L_{eff}} \int_0^L e^{G(z) - i\xi C(z)} dz, \quad (14)$$

then becomes essentially a real-valued number, when Eqs. (12) and (13) are applied, because

$$\eta(\xi) = \frac{1}{L_{eff}} \int_0^{L/2} [e^{G(z) - i\xi C(z)} + e^{G(L-z) - i\xi C(L-z)}] dz \approx \frac{1}{L_{eff}} \int_0^{L/2} 2e^{G(z)} \cos[\xi C(z)] dz. \quad (15)$$

10 This means that, for the case of transmission with the symmetric dispersion map, we have

$$\eta(\xi) \approx \eta(\xi)^*. \quad (16)$$

Based on a perturbation approach, we can express the nonlinear distortion on the E-field of an optical signal (E) after the transmission in the frequency domain as

$$\mathcal{E}(L, \omega) = i \frac{8}{9} \gamma P_0 L_{eff} \int_{-\infty}^{+\infty} d\omega_1 \int_{-\infty}^{+\infty} d\omega_2 \eta(\omega_1 \omega_2) E(\omega + \omega_1) E(\omega + \omega_2) E^*(\omega + \omega_1 + \omega_2), \quad (17)$$

15 where i is the imaginary unit, $*$ denotes complex conjugate, P_0, γ are respectively the fiber nonlinear Kerr coefficient and mean average signal launch power into each fiber span. This constitutes the nonlinear distortion on the E-field of a first pre-dispersion compensated phase-conjugated optical variant.

20 Since at least two pre-dispersion compensated phase-conjugated optical variants are transmitted according to embodiments of the invention, we can also express the nonlinear distortion on the E-field of the second pre-dispersion compensated phase-conjugated optical variant (E^*), (i.e., the twin wave of the first optical signal (E)) as

$$\begin{aligned}
\delta E^*(L, \omega) &= i \frac{8}{9} \mathcal{P}_0 L_{eff} \int_{-\infty}^{+\infty} d\omega_1 \int_{-\infty}^{+\infty} d\omega_2 \eta(\omega_1 \omega_2) E^*(\omega + \omega_1) E^*(\omega + \omega_2) E(\omega + \omega_1 + \omega_2) \\
&= [-i \frac{8}{9} \mathcal{P}_0 L_{eff} \int_{-\infty}^{+\infty} d\omega_1 \int_{-\infty}^{+\infty} d\omega_2 \eta^*(\omega_1 \omega_2) E(\omega + \omega_1) E(\omega + \omega_2) E^*(\omega + \omega_1 + \omega_2)]^* \\
&\approx [-\delta E(L, \omega)]^*
\end{aligned} \tag{18}$$

In the last derivation of the above equation, we use the fact that $\eta(\omega_1 \omega_2)$ is essentially real-valued, or $\eta(\omega_1 \omega_2) \approx \eta(\omega_1 \omega_2)^*$, based on Eq. (16). The above equation reveals that the nonlinear distortions experienced by two phase-conjugated optical variants are opposite to each other or anti-correlated (after their phase conjugation relation is removed), i.e.,

$$\delta E(L, \omega) \approx -[\delta E^*(L, \omega)]^* \tag{19}$$

So, the full cancellation of nonlinear distortions upon coherent superposition of the received phase-conjugated optical variants is evident from

$$E(L) + [E^*(L)]^* = [E + \delta E(L)] + [E^* + \delta E^*(L)]^* \approx 2E \tag{20}$$

It is remarkable that the above cancellation of nonlinear distortions is achieved even in the presence of large dispersion during fiber transmission (because the nonlinear distortions at different link locations are different due to the different accumulated dispersion values at these locations), when an appropriate amount of dispersion is induced on the phase-conjugated optical variants at the transmitter side through pre-dispersion-compensation to make the link dispersion map symmetric about zero dispersion.

These two pre-dispersion-compensated phase-conjugated optical variants are transmitted over an optical transmission link in different dimensions, e.g., in one or more of the time of transmission, spatial localization, polarization of light, optical carrier wavelength, and subcarrier frequency. For example, a first transmission of an optical symbol using a first (e.g., X) polarization and a second transmission of that same optical symbol using a second (e.g., Y) polarization represent two different optical variants of the bit-word that the optical symbol encodes. As a second example, a first transmission of an optical symbol at time t_1 and a second transmission of that same optical symbol at

time $t_2 > t_1$ represent two different optical variants of the bit-word that the optical symbol encodes. As a third example, a first transmission of an optical symbol using carrier wavelength λ_1 and a second (e.g., concurrent) transmission of that optical symbol using carrier wavelength λ_2 similarly represent two different optical variants of the bit-word that the optical symbol encodes. As a fourth example, a first transmission of an optical symbol via a first propagation path of a multipath fiber or fiber-optic cable (e.g., via a first core of a multi-core fiber or a first guided mode of a multi-mode fiber) and a second transmission of that optical symbol via a second propagation path of that multipath fiber or fiber-optic cable (e.g., via a second core of the multi-core fiber or a second guided mode of the multi-mode fiber) represent two different optical variants of the bit-word that the optical symbol encodes.

Note that, in each of these examples, the two corresponding optical variants are described as differing from one another in the parameters of just one degree of freedom. However, optical variants may differ from one another in the parameters of two or more degrees of freedom, such as: (i) polarization and time; (ii) time and space; (iii) time and wavelength; (iv) space and wavelength; (v) space and polarization; (vi) wavelength and polarization; (vii) time, space, and wavelength; (viii) time, space, and polarization; (ix) time, wavelength, and polarization; (x) space, wavelength, and polarization; or (xi) time, space, wavelength, and polarization.

The concept of optical variants also applies to (i) optical symbol sequences that carry multiple bit-words and (ii) optical signals that carry the same bit-word using different optical symbols. Further, more than two phase-conjugated optical variants may be transmitted/received over an optical path according to the principles of the invention. Assuming that the E-field of an optical signal intended for transmission is E , the E-field of the third, fourth, etc. optical variant can be either E or E^* , where $*$ denotes complex conjugate. As described above, optical variants are complex conjugates when they are equivalent after removal of a constant phase offset and /or time delay. Other pertinent features of “optical variants” will become more fully apparent, by way of example, from the following more detailed description that is given below in reference to FIGs. 1-7.

Herein, the terms “optical variants” and phase-conjugated optical variants” will be used to refer to optical variants that have been phase-conjugated, variants that have been phase-conjugated and pre-dispersion compensated, and variants that have been pre-dispersion compensated by opposite dispersions and then phase-conjugated.

5 Various embodiments rely on an inventive concept, according to which the receiver adds, in a phase-coherent manner, the electrical signals corresponding to at least two phase-conjugated optical variants, which may be pre-dispersion-compensated phase-conjugated optical variants, of the same symbol stream prior to de-modulation and de-coding. Each pair of phase-conjugated variants are conveyed from the transmitter to the
10 receiver on orthogonal transmission paths or dimensions, but experience similar nonlinear effects, which in effect impart opposite nonlinear distortions on these variants when the phase conjugation between the pair is removed. Accordingly, while the number of phase-conjugated optical variants utilized in any one embodiment may be even or odd, the use of a larger number of phase-conjugated optical variants is preferable to minimize
15 nonlinear effects when the number is odd.

FIG. 1 shows a block diagram of an optical transmission system **100** according to one embodiment of the invention. System **100** has an optical transmitter **110** that is configured to transmit optical variants that differ from each other in polarization or time, or both. System **100** also has an optical receiver **190** that is configured to process the
20 received optical variants to recover the corresponding original data in a manner that reduces the BER compared to the BER attainable without the use of optical variants. Transmitter **110** and receiver **190** are connected to one another via an optical transmission link **140**.

Transmitter **110** receives an input stream **102** of payload data and applies it to a
25 digital signal processor (DSP) **112**. Processor **112** processes input stream **102** to generate digital signals **114₁-114₄**. In each signaling interval (time slot), signals **114₁** and **114₂** carry digital values that represent the in-phase (I) component and quadrature (Q) component, respectively, of a corresponding constellation symbol intended for transmission using X-polarized light. Signals **114₃** and **114₄** similarly carry digital values

that represent the I and Q components, respectively, of the corresponding constellation symbol intended for transmission using Y-polarized light.

An electrical-to-optical (E/O) converter (also sometimes referred to as a front end) **116** of transmitter **110** transforms digital signals **114₁-114₄** into a modulated optical output signal **130**. More specifically, digital-to-analog converters (DACs) **118₁** and **118₂** transform digital signals **114₁** and **114₂** into an analog form to generate drive signals I_X and Q_X , respectively. Drive signals I_X and Q_X are then used, in a conventional manner, to drive an I-Q modulator **124_X**. Based on drive signals I_X and Q_X , I-Q modulator **124_X** modulates an X-polarized beam **122_X** of light supplied by a laser source **120_X**, thereby generating a modulated optical signal **126_X**.

DACs **118₃** and **118₄** similarly transform digital signals **114₃** and **114₄** into an analog form to generate drive signals I_Y and Q_Y , respectively. Based on drive signals I_Y and Q_Y , an I-Q modulator **124_Y** modulates a Y-polarized beam **122_Y** of light supplied by a laser source **120_Y**, thereby generating a modulated optical signal **126_Y**. A polarization beam combiner **128** combines modulated optical signals **126_X** and **126_Y** to generate optical output signal **130**.

In a representative configuration, processor **112** generates digital signals **114₁-114₄** so that, for each bit-word to be transmitted to receiver **190**, optical output signal **130** contains at least two phase-conjugated optical variants carrying that bit-word. The at least two phase-conjugated optical variants may be pre-dispersion-compensated phase conjugated optical variants. Conceptually, this set of pre-dispersion-compensated phase-conjugated optical variants can be viewed as comprising one or more overlapping and/or non-overlapping subsets. For example, there might be a subset consisting of two or more pre-dispersion-compensated phase-conjugated optical variants, in which the pre-dispersion-compensated phase-conjugated optical variants have the same polarization, but different temporal positions in signal **130**. Alternatively or in addition, there might be another subset consisting of two pre-dispersion-compensated phase-conjugated optical variants, in which the pre-dispersion-compensated phase-conjugated optical variants have the same temporal position (the same time slot) in signal **130**, but different polarizations.

Furthermore, there might be yet another subset consisting of pre-dispersion-compensated phase-conjugated optical variants, in which the pre-dispersion-compensated phase-conjugated optical variants have different temporal positions in signal **130** and different polarizations.

- 5 In one embodiment, two pre-dispersion-compensated phase-conjugated optical variants are carried by orthogonal polarization components. In this case, signals **114₁**, **114₂**, **114₃**, and **114₃** can be arranged to meet the following conditions

$$\begin{aligned} I_{x,Pre}(t) &= \text{real}(E_{x,Pre}(t)), & Q_{x,Pre}(t) &= \text{imag}(E_{x,Pre}(t)), \\ I_{y,Pre}(t) &= \text{real}(E_{y,Pre}(t)), & Q_{y,Pre}(t) &= \text{imag}(E_{y,Pre}(t)), \end{aligned} \quad (21)$$

- where $E_{x,Pre}$ and $E_{y,Pre}$ are the E-fields of pre-dispersion-compensated phase-conjugated optical variants

$$\begin{aligned} E_{x,Pre}(t) &= H_{Pre}(t) \otimes E(t), \\ E_{y,Pre}(t) &= H_{Pre}(t) \otimes E^*(t - \tau) \end{aligned} \quad (22)$$

where $H_{Pre}(t)$ is the time response of the pre-dispersion-compensator. As discussed before, the pre-dispersion-compensation can be implemented in the frequency domain, using, e.g., the overlap-and-add approach.

- 15 The processor **112** may also add pilot symbols and/or pilot-symbol sequences to each of signals **114₁**, **114₂**, **114₃**, and **114₃**. One purpose of the added pilot symbols and/or pilot-symbol sequences is to form an optical frame having a well-defined structure. This structure can be used at receiver **190** to distinguish the optical symbols corresponding to the payload data from the pilot symbols/sequences, and to ensure the
- 20 phase alignment between the optical variants. The pilot symbols/sequences can then be used to perform one or more of (i) time synchronization, (ii) channel estimation and compensation, (iii) frequency estimation and compensation, and (iv) phase estimation and compensation. An enabling description of possible frame structures and suitable pilot symbols/sequences can be found, e.g., in commonly owned U.S. Patent Application
- 25 Serial No. 12/964,929 (filed on 12-10-2010), which is incorporated herein by reference in its entirety.

System **100** has an optical add-drop multiplexer (OADM) configured to add signal **130**, as known in the art, to other optical signals that are being transported via optical transmission link **140**. Link **140** is illustratively shown as being an amplified link having a plurality of optical amplifiers **144** configured to amplify the optical signals that are being transported through the link, e.g., to counteract signal attenuation. Note that an optical link that does not have optical amplifiers can alternatively be used as well. After propagating the intended length of link **140**, signal **130** is dropped from the link via another optical add-drop multiplexer, OADM **146**, and directed to receiver **190** for processing. Note that the optical signal applied to receiver **190** by OADM **146** is labeled **130'**, which signifies the fact that, while in transit between transmitter **110** and receiver **190**, signal **130** may accumulate noise and other signal distortions due to various linear effects and nonlinear effects in the optical fiber. One type of a fiber nonlinear effect is intra-channel four-wave mixing (IFWM), which is a function of the phases and amplitudes of the corresponding optical symbols. Another type of a fiber nonlinear effect is inter-channel cross-phase modulation (XPM) caused by neighboring wavelength-division multiplexed (WDM) channels.

Receiver **190** has a front-end circuit **172** comprising an optical-to-electrical (O/E) converter **160**, four analog-to-digital converters (ADCs) **166₁-166₄**, and an optical local oscillator (OLO) **156**. O/E converter **160** has (i) two input ports labeled S and R and (ii) four output ports labeled 1 through 4. Input port S receives optical signal **130'**. Input port R receives an optical reference signal **158** generated by optical local oscillator **156**. Reference signal **158** has substantially the same optical-carrier frequency (wavelength) as signal **130'**. Reference signal **158** can be generated, e.g., using a tunable laser controlled by a wavelength-control loop (not explicitly shown in FIG. 1) that forces an output wavelength of the tunable laser to closely track the carrier wavelength of signal **130'**.

O/E converter **160** operates to mix input signal **130'** and reference signal **158** to generate eight mixed optical signals (not explicitly shown in FIG. 1). O/E converter **160** then converts the eight mixed optical signals into four electrical signals **162₁-162₄** that are indicative of complex values corresponding to the two orthogonal-polarization

components of signal **130'**. For example, electrical signals **162₁** and **162₂** may be an analog in-phase signal and an analog quadrature-phase signal, respectively, corresponding to the X-polarization component of signal **130'**. Electrical signals **162₃** and **162₄** may similarly be an analog in-phase signal and an analog quadrature-phase signal, respectively, corresponding to the Y-polarization component of signal **130'**.

In one embodiment, O/E converter **160** is a polarization-diverse 90-degree optical hybrid (PDOH) with four balanced photo-detectors coupled to its eight output ports. Additional information on various O/E converters that can be used to implement O/E converter **160** in various embodiments of system **100** are disclosed, e.g., in U.S. Patent Application Publication Nos. 2010/0158521 and 2011/0038631, and International Patent Application No. PCT/US09/37746 (filed on 03-20-2009), all of which are incorporated herein by reference in their entirety.

Each of electrical signals **162₁-162₄** generated by O/E converter **160** is converted into digital form in a corresponding one of ADCs **166₁-166₄**. Optionally, each of electrical signals **162₁-162₄** may be amplified in a corresponding amplifier (not explicitly shown) prior to the resulting signal being converted into digital form. Digital signals **168₁-168₄** produced by ADCs **166₁-166₄** are processed by a digital signal processor (DSP) **170**, e.g., as further described below in reference to FIG. 3, to recover the data of the original input stream **102** applied to transmitter **110**.

While the transmitter **110** of the illustrated system **100** is shown as having the ability to transmit a polarization multiplexed optical signal, as noted above, phase conjugated optical variants may be separated in time. According, in one embodiment, transmitter **110** includes hardware for generating a single polarization, for example X polarized light. In that embodiment, transmitter DSP **112** processes input stream **102** to generate digital signals **114₁ - 114₂**, which are converted to analog and modulated to provide a first phase-conjugated optical variant. At a later time, transmitter DSP **112** generates a second set of digital signals **114₁ - 114₂** for the processed input stream which digital signals are converted to analog and modulated to provide a second phase-conjugated optical variant according to the principles of the invention.

FIG. 2 shows a flowchart of a signal-processing method **200** that can be employed by processor **112** (FIG. 1) to generate digital signals **114₁-114₄** according to one embodiment of the invention where pre-dispersion-compensated phase-conjugated optical variants are carried on two orthogonal polarization states of a same wavelength channel.

At step **201** of method **200**, payload data **102** are processed to obtain the payload signal sequence, $E(t)$, using a given modulation format. The modulation format used can be selected from the group consisting of amplitude-shift keyed (ASK), phase-shift keyed (PSK), or quadrature-amplitude modulation (QAM) signals, such as 8-QAM and 16-QAM, or any suitable combination thereof. Other modulation formats may also be utilized.

At step **202** of method **200**, the payload signal sequence $E(t)$ and its phase-conjugated variant $E^*(t-\tau)$ are respectively assigned to the x-polarization and y-polarization components of the optical signal to be modulated.

At step **203** of method **200**, training symbols and pilot symbols are inserted to aid the recovery of the phase-conjugated optical variants at receiver **190**.

At step **204** of method **200**, pre-dispersion compensation is applied to the E-fields of both x- and y-polarization components of the optical signal to be modulated. The amount of dispersion induced by the pre-dispersion compensation may be about $-AD_{PW}/2$, where AD_{PW} is the power-weighted accumulated dispersion of optical fiber transmission link **140**. In one embodiment, the amount of dispersion induced by the pre-dispersion compensation is preferably about $-AD_{PW}/2$, where AD_{PW} is the power-weighted accumulated dispersion of optical fiber transmission link **140**. The pre-dispersion compensation can be implemented in the frequency domain using, e.g., the overlap-and-add approach. In certain embodiments, no pre-dispersion compensation is employed such that step 204 is optional. In other embodiments, the order of performance of phase conjugation and pre-dispersion compensation is switched. For example, two pre-dispersion-compensated phase conjugated optical variants may be formed by 1) generating (E, E^*) first and then compensating each by a same amount of dispersion D , or

(2) generating E, and compensating it by D for one variant; and compensating E by $-D$, and taking the complex conjugate to obtain the other variant.

At step **205** of method **200**, the digital representations of the real and imaginary parts of the E-field of the x-polarization component are converted into analog waveforms by DACs **118₁** and **118₂**. At the same time, the digital representations of the real and imaginary parts of the E-field of the y-polarization component are converted into analog waveforms by DACs **118₃** and **118₄**.

FIG. 3 shows a flowchart of a signal-processing method **300** that can be employed by processor **170** (FIG. 1) to recover data stream **102** from digital signals **168₁-168₄** according to one embodiment of the invention where pre-dispersion- compensated phase-conjugated optical variants are carried on two orthogonal polarization states of a same wavelength channel.

At step **301** of method **300**, digital signals **168₁-168₄** are processed to construct two received optical fields corresponding to two orthogonal polarization components, $E_{x',RX}(t)$ and $E_{y',RX}(t)$.

At step **302** of method **300**, post-dispersion compensation is applied to the E-fields of both x'- and y'-polarization components of the received optical signal. The amount of dispersion induced by the post-dispersion compensation is preferably chosen to bring the overall dispersion experienced by the signal variants to essentially zero. The post-dispersion compensation can be implemented in the frequency domain, e.g., by using the overlap-and-add approach.

At step **303** of method **300**, digital signal processing is applied to achieve time and frequency synchronization. In a representative implementation, the time-synchronization procedure of step **303** relies on certain properties of pilot-symbol sequences to determine the start of each optical frame. The known structure of the optical frame can then be used to identify time slots that have digital samples and/or digital-signal portions corresponding to the optical symbols carrying the payload data. The frequency-synchronization procedure of step **303** may perform electronic estimation and compensation of a mismatch between the carrier-frequency of input signal **130'** and

the frequency of reference signal **158** (see FIG. 1). After the frequency offset is determined, frequency-mismatch can be compensated, e.g., by applying to each digital sample a phase shift equal to the frequency offset multiplied by 2π and the time elapsed between the start of the frame and the temporal position of the digital sample.

5 At step **304** of method **300**, additional signal processing is applied to achieve channel estimation and compensation, and phase estimation and compensation to recover the E-fields of the original x- and y-polarization components, $E_x(t)$ and $E_y(t)$, as assigned at transmitter **110**. The channel-estimation/compensation procedure of step **304** performs electronic estimation and compensation of the phase and amplitude distortions imposed
10 by optical fiber transmission link **140**, due to effects such as chromatic dispersion and polarization-mode dispersion. In one embodiment, the channel estimation relies on digital samples corresponding to pilot symbols to determine the channel-response function, H , of optical fiber transmission link **140**. The inverse channel-response function H^{-1} is then applied to the digital samples corresponding to payload data to perform channel
15 compensation. In another embodiment, the channel estimation relies on blind adaptive equalization.

 At step **304**, phase estimation and phase compensation are also performed, e.g., through the assistance of pilot symbols to correct or compensate for slowly changing phase shifts between input signal **130'** and reference signal **158** (FIG. 1). Various
20 methods that can be used for this purpose are disclosed, e.g., in U.S. Patent Application Publication Nos. 2008/0152361 and 2008/0075472 and U.S. Patent No. 7,688,918, all of which are incorporated herein by reference in their entirety.

In this manner the plurality of digital electrical signals are processed to generate a set of complex values representing a modulated payload symbol.

25 In another embodiment, the channel estimation relies on blind adaptive equalization and step **304** additionally aligns the streams in time (τ) and phase (in the case of arbitrary $\pi/2$ phase rotations). In one embodiment, a single (joint) frequency and phase tracking algorithm is utilized for the variants.

At step **305**, the recovered E-fields of phase-conjugated optical variants are further processed to remove the phase conjugation between them, followed by coherent summation. The coherent summation forms an aggregate constellation that is used for further processing. For the transmitter embodiment described by Eq. (22), step **305** is configured to obtain the original optical signal intended for transmission (omitting a trivial scaling factor) as follows

$$E(t) = E_x(t) + E_y(t + \tau)^* \quad (23)$$

At step **306**, the recovered original optical signal field intended for transmission, $E(t)$, is renormalized, and either directly or with reduced resolution fed into a soft-decision FEC, or hard symbol decisions are made and symbol-to-bit demapping is done, followed by hard-decision FEC to obtain payload data **102**.

FIG. 4 shows a block diagram of an optical transmission system **400** according to another embodiment of the invention. System **400** has an optical transmitter **410** that is configured to transmit pre-dispersion-compensated phase-conjugated optical variants that differ from each other in one or more dimensions such as time, space, polarization, carrier wavelength, or subcarrier frequency in frequency-division multiplexed (FDM) systems. System **400** also has an optical receiver **490** that is configured to process the received optical variants to recover the corresponding original data in a manner that reduces the BER compared to the BER attainable without the use of optical variants. Transmitter **410** and receiver **490** are connected to one another via an optical fiber transmission link **440**.

Transmitter **410** has a front-end circuit **416** having L electrical-to-optical (E/O) converters **116₁-116_L** (also see FIG. 1), each configured to use a different respective carrier wavelength selected from a specified set of wavelengths λ_1 - λ_L . Transmitter **410** further has a wavelength multiplexer (MUX) **420** configured to combine optical output signals **418₁-418_L** generated by E/O converters **116₁-116_L**, respectively, and apply a resulting WDM signal **430** to an OADM **436** for adding it to the signals that are being transmitted through fiber link **440**.

Each of E/O converters **116₁-116_L** generates its respective optical output signal **418** based on a corresponding set **414** of digital signals supplied by a DSP **412**. Each signal set **414** has four electronic signals that are analogous to digital signals **114₁-114₄** (FIG. 1). Signal sets **414₁-414_L** are generated by DSP **412** based on an input data stream **402**. When each of E/O converters **116₁-116_L** generates two pre-dispersion-compensated phase-conjugated optical variants, the total number of pre-dispersion-compensated phase-conjugated optical variants is $2L$.

After propagating through link **440**, signal **430** is dropped from the link (as signal **430'**) via another optical add-drop multiplexer, OADM **446**, and directed to receiver **490** for processing. Receiver **490** has a front-end circuit **472** comprising a wavelength de-multiplexer (DEMUX) **450** and L front-end circuits **172₁-172_L** (also see FIG. 1). Wavelength de-multiplexer (DEMUX) **450** is configured to de-multiplex signal **430'** into its constituent WDM components **452₁-452_L**, each having a corresponding one of carrier wavelengths λ_1 - λ_L . Each of front-end circuits **172₁-172_L** then processes the corresponding one of signals **452₁-452_L**, as described above in reference to FIG. 1, to generate a corresponding one of sets **468₁-468_L** of digital signals, with each set consisting of four digital signals analogous to digital signals **168₁-168₄**, respectively (see FIG. 1).

Signal sets **468₁-468_L** generated by front-end circuit **472** are processed by a DSP **470** to recover the data of original input stream **402** applied to transmitter **410**.

FIG. 5 shows a block diagram of an optical transmission system **500** according to yet another embodiment of the invention. System **500** has an optical transmitter **510** that can be configured to transmit optical variants, including phase-conjugated optical variants and pre-dispersion-compensated phase-conjugated optical variants, that differ from each other in one or more dimensions such as time, polarization, and space (as represented by a plurality of different propagation paths). System **500** also has an optical receiver **590** that is configured to process the received optical variants to recover the corresponding original data in a manner that reduces the BER compared to the BER attainable without the use of optical variants. Transmitter **510** and receiver **590** are

connected to one another via an optical fiber transmission link comprising a multi-core fiber **540**, different cores of which provide the plurality of propagation paths.

Transmitter **510** has a front-end circuit **516** having L electrical-to-optical (E/O) converters **116₁-116_J** (also see FIG. 1), each configured to use a different respective spatial path. Transmitter **510** further has an optical coupler **526** configured to couple optical output signals **518₁-518_J** generated by E/O converters **116₁-116_J**, respectively, into corresponding cores of multi-core fiber **540**.

Each of E/O converters **116₁-116_J** generates its respective optical output signal **418** based on a corresponding set **514** of digital signals supplied by a DSP **512**. Each signal set **514** has four electronic signals that are analogous to digital signals **114₁-114₄** (FIG. 1). Signal sets **514₁-514_J** are generated by DSP **412** based on an input data stream **402**. When each of E/O converters **116₁-116_J** generates one *vector* optical variant, the total number of phase-conjugated optical variants is then J.

After propagating through multi-core fiber **540**, signal **530** is applied (as signal **530'**) to receiver **590** for processing. Receiver **590** has an optical coupler **546** and a front-end circuit **572** comprising J front-end circuits **172₁-172_J** (also see FIG. 1). Optical coupler **546** is configured to direct light from each core of multi-core fiber **540** to a corresponding one of front-end circuits **172₁-172_J**. Each of front-end circuits **172₁-172_J** then processes the signal received from optical coupler **546**, as described above in reference to FIG. 1, to generate a corresponding one of sets **568₁-568_J**, each having four digital signals analogous to digital signals **168₁-168₄**, respectively (see FIG. 1). In one embodiment, front-end circuits **172₁-172_J** in receiver **590** share a single common OLO **156** (see FIG. 1).

Signal sets **568₁-568_J** generated by front-end circuit **572** are processed by DSP **570** to recover the data of original input stream **502** applied to transmitter **510**.

FIG. 6 shows a flowchart of a transmitter signal-processing method **600** that can be employed by processor **412** (FIG. 4) or **512** (FIG. 5) to generate analog drive signals **414₁-468_L** or **514₁-514_J** according to another embodiment of the invention where optical variants, including phase-conjugated vector optical variants and pre-dispersion-

compensated phase-conjugated vector optical variants, are carried by wavelength channels or by different spatial paths.

At step **601** of method **600**, payload data **402** or **502** are processed to obtain the payload signal sequence, $E(t)$, using a given modulation format.

5 At step **602** of method **600**, the payload signal sequence $E(t)$ is de-interleaved into two equal-length sequences, $E_{\text{even}}(t)$ and $E_{\text{odd}}(t)$.

At step **603** of method **600**, $E_{\text{even}}(t)$ and $E_{\text{odd}}(t)$ are respectively assigned to the x-polarization and y-polarization components of a first vector optical variant $(E_{1x}, E_{1y})^T$, where $()^T$ denotes matrix transpose. At the same time, their complex conjugates, $E_{\text{even}}(t)^*$ and $E_{\text{odd}}(t)^*$ are respectively assigned to the x-polarization and y-polarization components of a second vector optical variant $(E_{2x}, E_{2y})^T$.

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At step **604** of method **600**, training symbols and pilot symbols are inserted to aid the recovery of the phase-conjugated optical variants at receiver **490** or **590**.

At step **605** of method **600**, pre-dispersion compensation applied to the E-fields of both x- and y-polarization components of the vector optical signal variants to be modulated. In one embodiment, the amount of dispersion induced by the pre-dispersion compensation is about $-AD/2$, where AD is the accumulated dispersion of optical fiber transmission link **440** or **540**. In another embodiment, the amount of dispersion induced by the pre-dispersion compensation is preferably about $-AD_{\text{PW}}/2$, where AD_{PW} is the power-weighted accumulated dispersion of optical fiber transmission link **440** or **540**. In another embodiment, no pre-dispersion compensation is undertaken, and optical variants that are phase-conjugated are provided to step **606**.

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At step **606** of method **600**, the digital representations of the real and imaginary parts of the E-fields of the x- and y- polarization components of each vector optical variant are output to the DACs imbedded in one of the E/O converters **116_I-116_L** (FIG. 4) or **116_I** and **118_J** (FIG. 5).

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FIG. 7 shows a flowchart of a receiver signal-processing method **700** that can be employed by processor **470** (FIG. 4) or **570** (FIG. 5) to recover data stream **102** from digital signals **468_I-468_L** or **568_I-568_J** according to another embodiment of the invention

where optical variants, including phase-conjugated optical variants and pre-dispersion-compensated phase-conjugated vector optical variants, are carried by wavelength channels or by different spatial paths.

Steps **701-704** are similar to steps **301-304**, but process E-fields received by at least two front ends for at least two vector signal variants. For the transmitter embodiment described by method **600**, step **705** may be configured to obtain the original interleaved optical signal intended for transmission as follows

$$\begin{aligned} E_{\text{even}}(t) &= E_{1x}(t) + E_{2x}(t)^*, \\ E_{\text{odd}}(t) &= E_{1y}(t) + E_{2y}(t)^*, \end{aligned} \quad (24)$$

where $E_{1x}(t)$ and $E_{1y}(t)$ are the recovered E-fields for front end 172₁, and $E_{2x}(t)$ and $E_{2y}(t)$ are the recovered E-fields for front end 172₂.

At step **706**, the recovered original optical signal field, $E(t)$, is obtained by interleaving the recovered even and odd ports of the original signal field, $E_{\text{even}}(t)$ and $E_{\text{odd}}(t)$, from step **705**.

At step **707**, the recovered original optical signal field, $E(t)$, is renormalized, demodulated, and FEC decoded to obtain payload data **102**.

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense.

Although phase-conjugated optical variants have been defined in the time domain, phase conjugation can also be realized in the frequency domain. As an example, two OFDM symbols can be phase-conjugated optical variants when the modulated subcarriers of the second OFDM symbol are complex conjugates of those of the first OFDM symbol. In effect, frequency-domain phase conjugation can be seen as time-domain phase conjugation plus time reversal.

Although system **500** (FIG. 5) has been described in reference to multi-core fiber **540**, it can be adapted for use with a set of parallel single-mode fibers, or with a multi-mode fiber, wherein different guided modes of the multi-mode fiber provide the spatial degrees of freedom for the generation and transmission of optical variants. Representative optical couplers that can be used in conjunction with the multi-mode fiber

in such a system are disclosed, e.g., in U.S. Patent Application Publication Nos. 2010/0329670 and 2010/0329671 and U.S. Patent Application Serial Nos. 12/986,468, filed on 01-07-2011, and 12/827,284, filed on 06-30-2010, all of which are incorporated herein by reference in their entirety.

5 In one embodiment, different cores of multi-core fiber **540** can be configured to concurrently transmit optical variants corresponding to different data, for example bit-words. In one embodiment, transmitter 510 is configured so that different cores of multi-core fiber **540** concurrently transmit optical variants corresponding to different bit-words. In another embodiment, transmitter 510 is configured with multi-core fiber **540** so that,
10 at any time, at least two cores of the multi-core fiber transmit optical variants corresponding to the same bit-word.

 Furthermore, system **500** can be modified in a relatively straightforward manner to use optical variants that differ from each other in one or more of time, polarization, carrier wavelength, and space. Transmitting phase-conjugated optical variants through
15 different spatial paths may be exploited to enhance the security of communication, e.g., by allowing for reliable communication only when at least two optical variants are simultaneously detected and coherently superimposed (to cancel out the nonlinear distortions caused on them).

 Moreover, transmitting phase-conjugated optical variants may be naturally
20 compatible with the use of low-noise phase-sensitive amplifiers based on the interaction between a signal and its phase-conjugated duplicate in parametric optical amplification, to improve communication immunity to both nonlinear distortions and the linear optical noise.

 In various alternative embodiments of methods **200**, **300**, **600**, and **700**, the order
25 of certain processing steps may be changed to differ from the order indicated in FIGs. 2, 3, 6, and 7, respectively.

 Various modifications of the described embodiments, as well as other
embodiments of the invention, which are apparent to persons skilled in the art to which
the invention pertains are deemed to lie within the principle and scope of the invention as
30 expressed in the following claims.

Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word "about" or "approximately" preceded the value of the value or range.

It will be further understood that various changes in the details, materials, and
5 arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.

The use of figure numbers and/or figure reference labels in the claims is intended to identify one or more possible embodiments of the claimed subject matter in order to
10 facilitate the interpretation of the claims. Such use is not to be construed as necessarily limiting the scope of those claims to the embodiments shown in the corresponding figures.

Although the elements in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise
15 imply a particular sequence for implementing some or all of those elements, those elements are not necessarily intended to be limited to being implemented in that particular sequence.

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the
20 embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term "implementation."

25 Also for purposes of this description, the terms "couple," "coupling," "coupled," "connect," "connecting," or "connected" refer to any manner known in the art or later developed in which energy is allowed to be transferred between two or more elements, and the interposition of one or more additional elements is contemplated, although not required. Conversely, the terms "directly coupled," "directly connected," etc., imply the
30 absence of such additional elements.

The present inventions may be embodied in other specific apparatus and/or methods. The described embodiments are to be considered in all respects as only illustrative and not restrictive. In particular, the scope of the invention is indicated by the appended claims rather than by the description and figures herein. All changes that come
5 within the meaning and range of equivalency of the claims are to be embraced within their scope.

A person of ordinary skill in the art would readily recognize that steps of various above-described methods can be performed by programmed computers. Herein, some embodiments are intended to cover program storage devices, e.g., digital data storage
10 media, which are machine or computer readable and encode machine-executable or computer-executable programs of instructions where said instructions perform some or all of the steps of methods described herein. The program storage devices may be, e.g., digital memories, magnetic storage media such as a magnetic disks or tapes, hard drives, or optically readable digital data storage media. The embodiments are also intended to
15 cover computers programmed to perform said steps of methods described herein.

The description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those of ordinary skill in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all
20 examples recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as
25 well as specific examples thereof, are intended to encompass equivalents thereof.

The functions of the various elements shown in the figures, including any functional blocks labeled as “processors,” may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a
30 single dedicated processor, by a single shared processor, or by a plurality of individual

processors, some of which may be shared. Moreover, explicit use of the term “processor” or “controller” should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, network processor, application specific integrated circuit (ASIC), field programmable gate array (FPGA), read only memory (ROM) for
5 storing software, random access memory (RAM), and non volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, any switches shown in the figures are conceptual only. Their function may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable
10 by the implementer as more specifically understood from the context.

It should be appreciated by those of ordinary skill in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flowcharts, flow
15 diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

CLAIMS

What is claimed is:

1. An apparatus comprising an optical transmitter, the optical transmitter comprising:
 - a processor configured to generate electronic representations of at least two pre-
 - 5 dispersion-compensated phase-conjugated optical variants carrying a same modulated payload data for transmission; and
 - at least one optical modulator for modulating the electronic representations, wherein an amount of dispersion induced on the pre-dispersion-compensated phase-conjugated optical variants depends on an accumulated dispersion (AD) of a transmission
 - 10 link through which the pre-dispersion-compensated phase-conjugated optical variants are to be transmitted.
2. The apparatus of claim 1 wherein the processor is configured to generate the electronic representations by convolving an E-field representation with a pre-dispersion-
- 15 compensation function.
3. The apparatus of claim 1 wherein the amount of dispersion induced on the pre-dispersion-compensated phase-conjugated optical variants is about $-AD/2$, where AD is the accumulated dispersion of the transmission link through which the pre-dispersion-
- 20 compensated phase-conjugated optical variants are to be transmitted.
4. The apparatus of claim 1 wherein the processor is configured to induce dispersion by electronically pre-compensating complex fields representing phase-conjugated optical variants.
- 25
5. The apparatus of claim 1 wherein the digital representations of the at least two pre-dispersion-compensated phase-conjugated optical variants are complex conjugates before being pre-dispersion compensated.

6. The apparatus of claim 1 further comprising:

an optical receiver for receiving versions of at least two pre-dispersion-compensated phase-conjugated optical variants.

5 7. The apparatus of claim 7 wherein the optical receiver is further configured to compensate for residual dispersion of the received versions of at least two pre-dispersion-compensated phase-conjugated optical variants.

8. The apparatus of claim 1 wherein transmitter is configured to transmitted the pre-dispersion-compensated phase-conjugated optical variants on different paths for a same receiver and with a signal quality such that the payload data cannot be decoded with detection of a single pre-dispersion compensated phase-conjugated optical variant, the method thereby providing security of communication between the transmitter and a receiver.

15

9. A method comprising:

generating, by a processor, digital representations of at least two pre-dispersion-compensated phase-conjugated optical variants carrying a same modulated payload data for transmission; and

20

modulating, by at least one optical modulator, the digital representations, wherein an amount of dispersion induced on the pre-dispersion compensated phase-conjugated optical variants depends on an accumulated dispersion (AD) of a transmission link through which the pre-dispersion compensated phase-conjugated optical variants are to be transmitted.

25

10. The method of claim 9 wherein generating the digital representations comprises:

convolving an E-field representation with a pre-dispersion-compensation function.

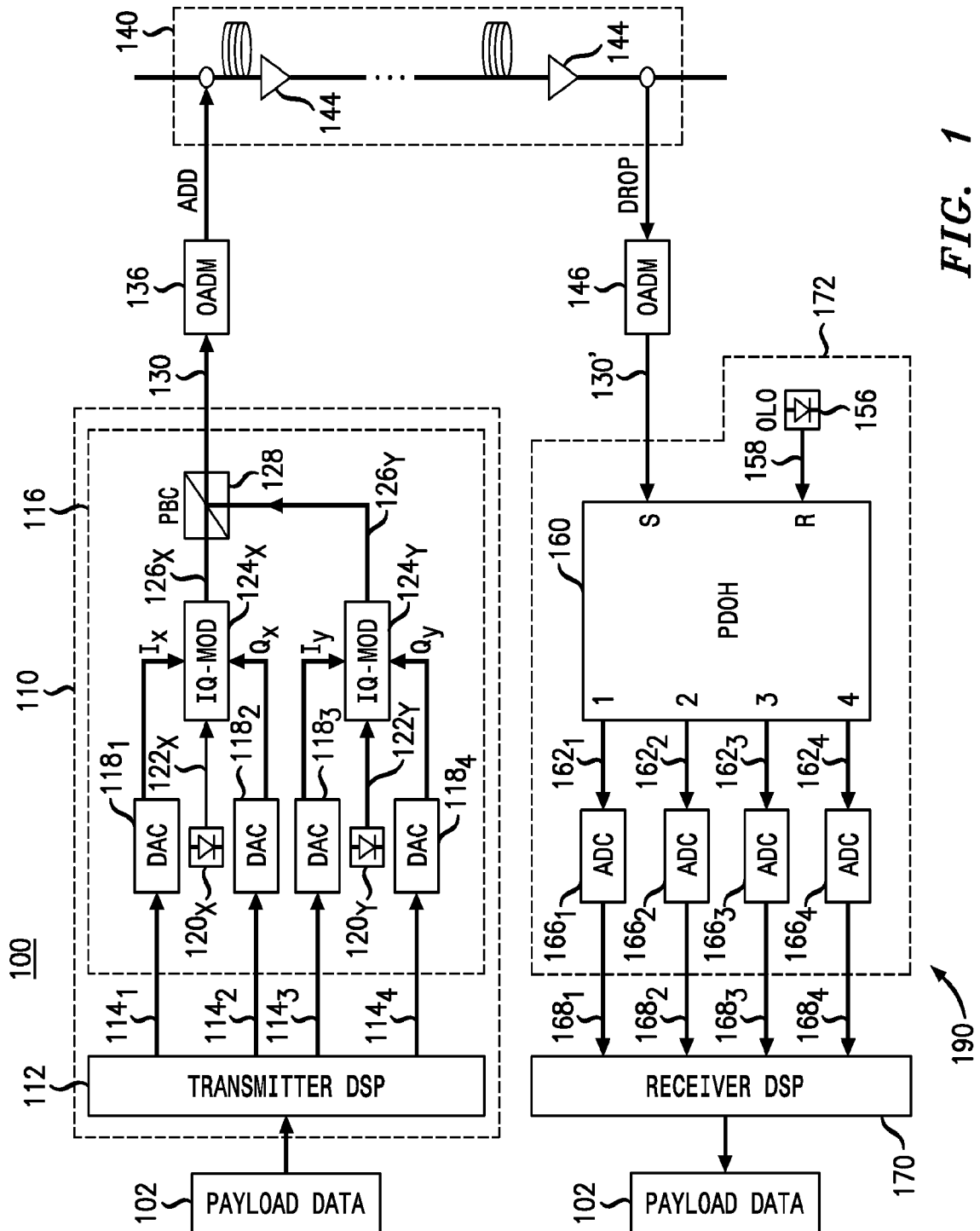


FIG. 1

200

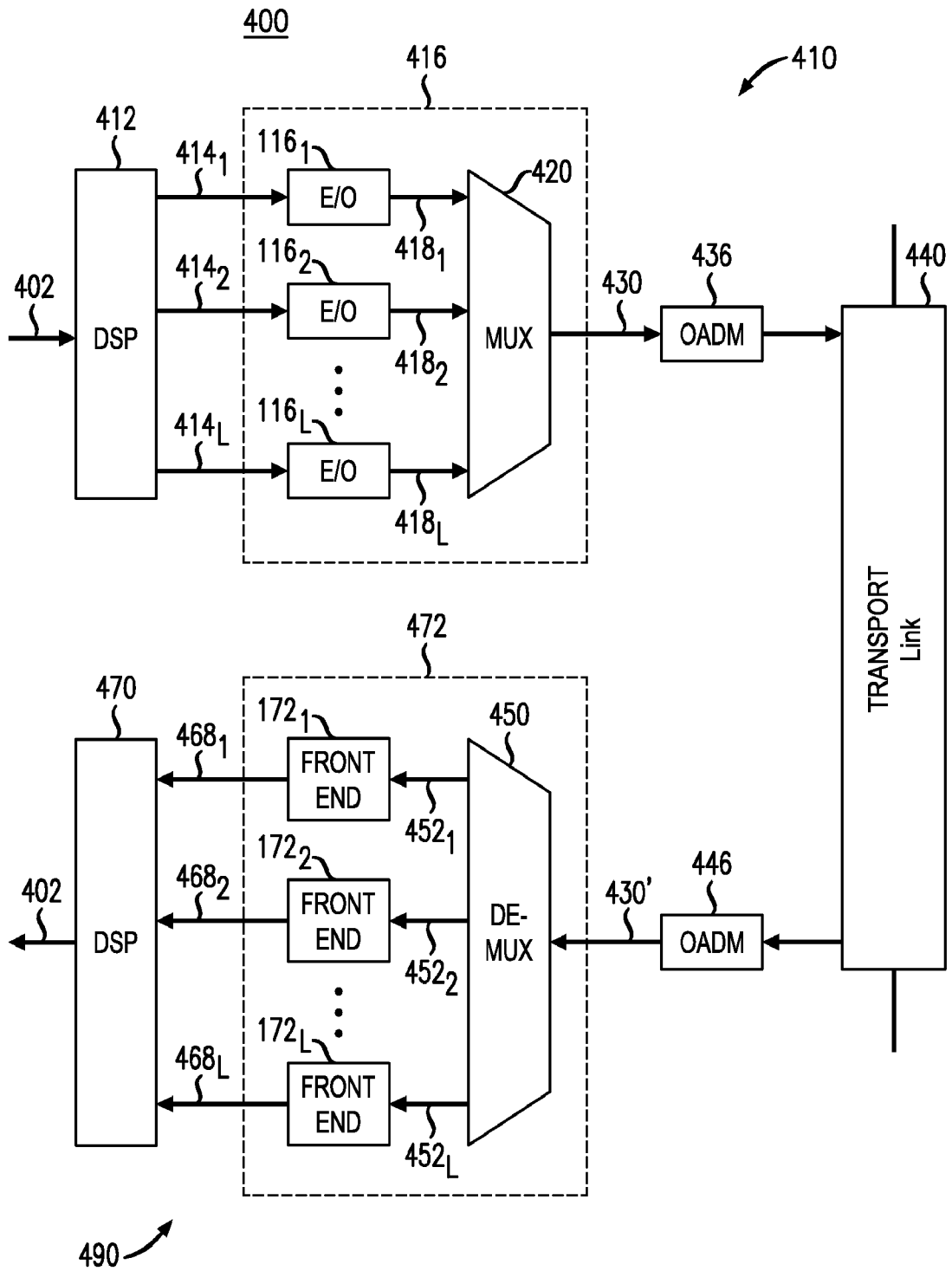
Obtain the payload signal sequence, $E(t)$		201
Let $E_x(t)=E(t)$	Let $E_y(t)=E(t - \tau)^*$	202
Add training symbols and pilots	Add training symbols and pilots	203
Perform pre-dispersion-compensation: $E_{x, Pre}(t)=H_{Pre}(t) \otimes E_x(t)$	Perform pre-dispersion-compensation: $E_{y, Pre}(t)=H_{Pre}(t) \otimes E_y(t)$	204
Output to two DACs: $I_{x, Pre}(t)=\text{real}[E_{x, Pre}(t)],$ $Q_{x, Pre}(t)=\text{imag}[E_{x, Pre}(t)],$	Output to two DACs: $I_{y, Pre}(t)=\text{real}[E_{y, Pre}(t)],$ $Q_{y, Pre}(t)=\text{imag}[E_{y, Pre}(t)],$	205

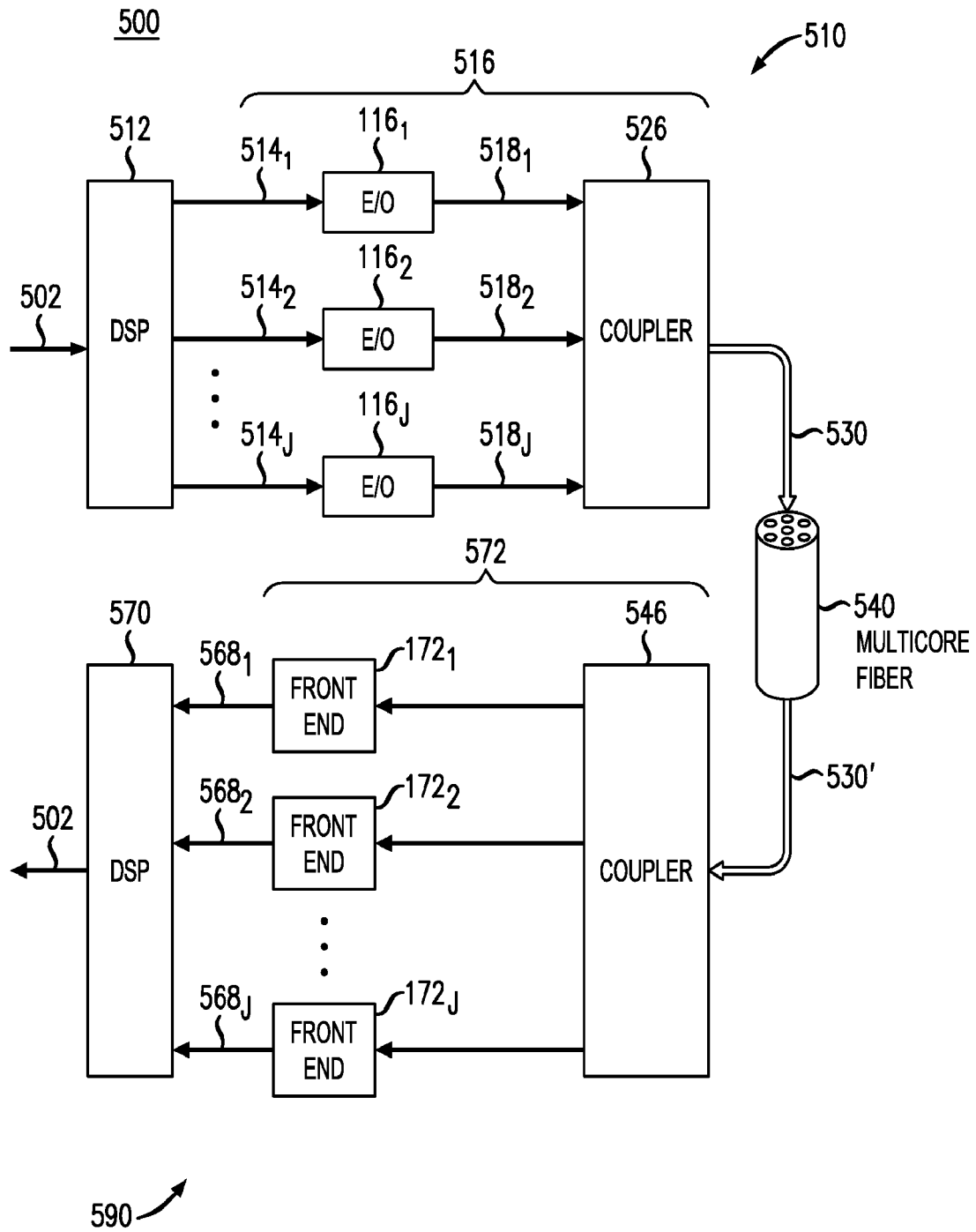
FIG. 2

300

Get the received E-field of one polarization: $E_{x',RX} = I_{x',RX} + j \cdot Q_{x',RX}$	Get the received E-field of one polarization: $E_{y',RX} = I_{y',RX} + j \cdot Q_{y',RX}$	301
Perform post-dispersion-compensation: $E_{x',Post} = H_{Post} \otimes E_{x',RX}$	Perform post-dispersion-compensation: $E_{y',Post} = H_{Post} \otimes E_{y',RX}$	302
Synchronization in time and frequency		303
Channel estimation and compensation to recover the original x- and y-fields: $E_x(t)$ and $E_y(t)$		304
Coherently superimposing $E_x(t)$ and $E_y(t)$ to obtain the payload signal sequence: $E(t) = E_x(t) + E_y(t + \tau)^*$		305
Renormalization, Demodulation and FEC decoding		306

FIG. 3

**FIG. 4**

**FIG. 5**

600

Obtain the payload signal sequence, $E(t)$				601
De-interleave $E(t)$ into two equal-length sequences, $E_{\text{even}}(t)$ and $E_{\text{odd}}(t)$				602
Let $E_{1x}(t) = E_{\text{even}}(t)$	Let $E_{1y}(t) = E_{\text{odd}}(t)$	Let $E_{2x}(t) = E_{\text{even}}(t)^*$	Let $E_{2y}(t) = E_{\text{odd}}(t)^*$	603
Add training symbols and pilots	Add training symbols and pilots	Add training symbols and pilots	Add training symbols and pilots	604
Perform pre-dispersion-compensation: $E_{1x, \text{Pre}}(t) = H_{\text{Pre}}(t) \otimes E_{1x}(t)$	Perform pre-dispersion-compensation: $E_{y, \text{Pre}}(t) = H_{\text{Pre}}(t) \otimes E_{1y}(t)$	Perform pre-dispersion-compensation: $E_{2x, \text{Pre}}(t) = H_{\text{Pre}}(t) \otimes E_{2x}(t)$	Perform pre-dispersion-compensation: $E_{2y, \text{Pre}}(t) = H_{\text{Pre}}(t) \otimes E_{2y}(t)$	605
Output to two DACs: $I_{1x, \text{Pre}}(t) = \text{real}[E_{1x, \text{Pre}}(t)]$, $Q_{1x, \text{Pre}}(t) = \text{imag}[E_{1x, \text{Pre}}(t)]$	Output to two DACs: $I_{y, \text{Pre}}(t) = \text{real}[E_{1y, \text{Pre}}(t)]$, $Q_{y, \text{Pre}}(t) = \text{imag}[E_{1y, \text{Pre}}(t)]$	Output to two DACs: $I_{2x, \text{Pre}}(t) = \text{real}[E_{2x, \text{Pre}}(t)]$, $Q_{2x, \text{Pre}}(t) = \text{imag}[E_{2x, \text{Pre}}(t)]$	Output to two DACs: $I_{2y, \text{Pre}}(t) = \text{real}[E_{2y, \text{Pre}}(t)]$, $Q_{2y, \text{Pre}}(t) = \text{imag}[E_{2y, \text{Pre}}(t)]$	606

FIG. 6

700

Get the received E-field of one polarization: $E_{1x', RX} = I_{1x', RX} + j \cdot Q_{1x', RX}$	Get the received E-field of the other polarization: $E_{1y', RX} = I_{1y', RX} + j \cdot Q_{1y', RX}$	Get the received E-field of one polarization: $E_{2x', RX} = I_{2x', RX} + j \cdot Q_{2x', RX}$	Get the received E-field of the other polarization: $E_{2y', RX} = I_{2y', RX} + j \cdot Q_{2y', RX}$	701
Perform post-dispersion-compensation: $E_{1x', Post} = H_{Post} \otimes E_{1x', RX}$	Perform post-dispersion-compensation: $E_{1y', Post} = H_{Post} \otimes E_{1y', RX}$	Perform post-dispersion-compensation: $E_{2x', Post} = H_{Post} \otimes E_{2x', RX}$	Perform post-dispersion-compensation: $E_{2y', Post} = H_{Post} \otimes E_{2y', RX}$	702
Synchronization in time and frequency				703
Channel estimation and compensation to recover the original x- and y-fields: $E_{1x}(t)$ and $E_{1y}(t)$		Channel estimation and compensation to recover the original x- and y-fields: $E_{2x}(t)$ and $E_{2y}(t)$		704
Coherently superimposing: $E_{even}(t) = E_{1x}(t) + E_{2x}(t)^*$, $E_{odd}(t) = E_{1y}(t) + E_{2y}(t)^*$,				705
Interleave $E_{even}(t)$ and $E_{odd}(t)$ to obtain the original payload symbol sequence $E(t)$				706
Renormalization, Demodulation and FEC decoding				707

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2012/055012

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/155
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 H04L

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, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1 341 322 A2 (NIPPON TELEGRAPH & TELEPHONE [JP]) 3 September 2003 (2003-09-03) paragraph [0070] - paragraph [0073] paragraph [0084] - paragraph [0086] figures 6A,6B,6C,7A,7B,15A,15B ----- -/--	1-10



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

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Date of the actual completion of the international search

26 November 2012

Date of mailing of the international search report

05/12/2012

Name and mailing address of the ISA/

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Petitit, Nicolas

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2012/055012

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CHONGJIN XIE ET AL: "Electronic nonlinearity compensation in 112-Gb/s PDM-QPSK optical coherent transmission systems", 36TH EUROPEAN CONFERENCE AND EXHIBITION ON OPTICAL COMMUNICATION : (ECOC 2010) ; TORINO, ITALY, 19 - 23 SEPTEMBER 2010, IEEE, PISCATAWAY, NJ, USA, 19 September 2010 (2010-09-19), pages 1-3, XP031789766, ISBN: 978-1-4244-8536-9 the whole document -----	1-10
A	GUPTA S ET AL: "Dispersion Penalty Mitigation Using Polarization Mode Multiplexing in Phase Diverse Analog Optical Links", OPTICAL FIBER COMMUNICATION/NATIONAL FIBER OPTIC ENGINEERS CONFERENCE, 2008. OFC/NFOEC 2008. CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 24 February 2008 (2008-02-24), pages 1-3, XP031391214, ISBN: 978-1-55752-856-8 the whole document -----	1-10
A	US 2008/279564 A1 (HAN YAN [US] ET AL) 13 November 2008 (2008-11-13) figures 1,2,3,4,5 paragraph [0013] - paragraph [0018] paragraph [0026] - paragraph [0028] -----	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2012/055012

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US 2008279564	A1	13-11-2008	NONE
