



US007167651B2

(12) **United States Patent**
Shpantzer et al.

(10) **Patent No.:** **US 7,167,651 B2**
(45) **Date of Patent:** **Jan. 23, 2007**

(54) **SYSTEM AND METHOD FOR CODE
DIVISION MULTIPLEXED OPTICAL
COMMUNICATION**

(75) Inventors: **Isaac Shpantzer**, Bethesda, MD (US);
Michael Tseytlin, Bethesda, MD (US);
Yaakov Achiam, Rockville, MD (US);
Aviv Salamon, Washington, DC (US);
Israel Smilanski, Rockville, MD (US);
Olga Ritterbush, Rockville, MD (US);
Pak Shing Cho, Gaithersburg, MD
(US); **Li Guoliang**, North Potomac,
MD (US); **Jacob Khurgin**, Baltimore,
MD (US); **Yehouda Meiman**, Rishon
Letzion (IL); **Alper Demir**, Jersey City,
NJ (US); **Peter Feldman**, Short Hills,
NJ (US); **Peter Kinget**, Summit, NJ
(US); **Nagendra Krishnapura**,
Hoboken, NJ (US); **Jaijeet**
Roychowdhury, Minneapolis, MN
(US); **Joseph Schwarzwald**,
Gaithersburg, MD (US); **Charles**
Sciabarra, Ellicott City, MD (US)

(73) Assignee: **CeLight, Inc.**, Silver Spring, MD (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 653 days.

(21) Appl. No.: **09/962,243**

(22) Filed: **Sep. 26, 2001**

(65) **Prior Publication Data**

US 2002/0145787 A1 Oct. 10, 2002

Related U.S. Application Data

(60) Provisional application No. 60/234,930, filed on Sep.
26, 2000.

(51) **Int. Cl.**

H04J 4/00 (2006.01)

H04B 10/00 (2006.01)

H04B 10/04 (2006.01)

H04B 10/06 (2006.01)

(52) **U.S. Cl.** **398/77; 398/74; 398/152;**
398/184; 398/205

(58) **Field of Classification Search** **398/74;**
398/77, 79, 152, 162, 184, 198, 205
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,060,312 A 10/1991 Delavaux

(Continued)

FOREIGN PATENT DOCUMENTS

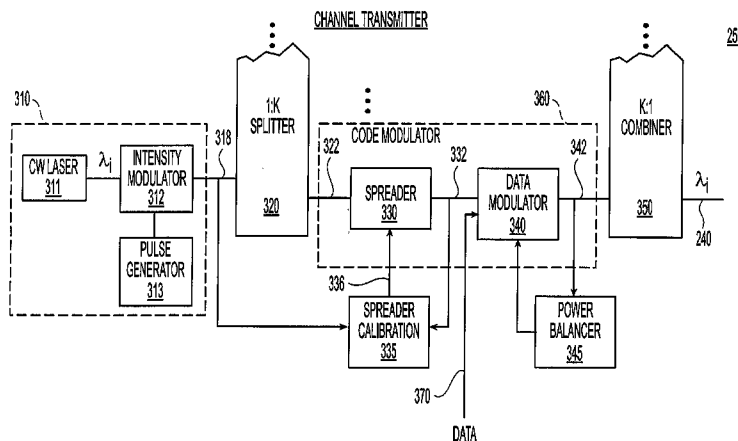
DE 3442988 6/1985

Primary Examiner—Dalzid Singh

(57) **ABSTRACT**

A system for optical communication forms a family of orthogonal optical codes modulated by a data stream. The orthogonal codes are formed by creating a stream of evenly spaced-apart pulses using a pulse spreader circuit and modulating the pulses in amplitude and/or phase to form a family of orthogonal optical code words, each representing a symbol. A spreader calibration circuit is used to ensure accurate timing and modulation. Each code word is further modulated by a predetermined number of data bits. The data modulation scheme splits a code word into H and V components, and further processes the components prior to modulation with data, followed by recombining with a polarization beam combiner. The data-modulated code word is then sent, along with others to receiver. The received signal is detected and demodulated with the help of a symbol synchronization unit which establishes the beginning and end of the code words. A polarization mode distortion compensator at the receiver cooperates with a state of polarization compensator at the transmitter to mitigate polarization distortion in the fiber.

18 Claims, 21 Drawing Sheets



Page 2

6,915,077	B1 *	7/2005	Lo	398/47
2004/0160661	A1	8/2004	Hurrell et al.	
2004/0208414	A1	10/2004	Lee et al.	

5,654,818	A	8/1997	Yao	
6,025,944	A *	2/2000	Mendez et al.	398/78
6,266,457	B1 *	7/2001	Jacob	385/11

* cited by examiner

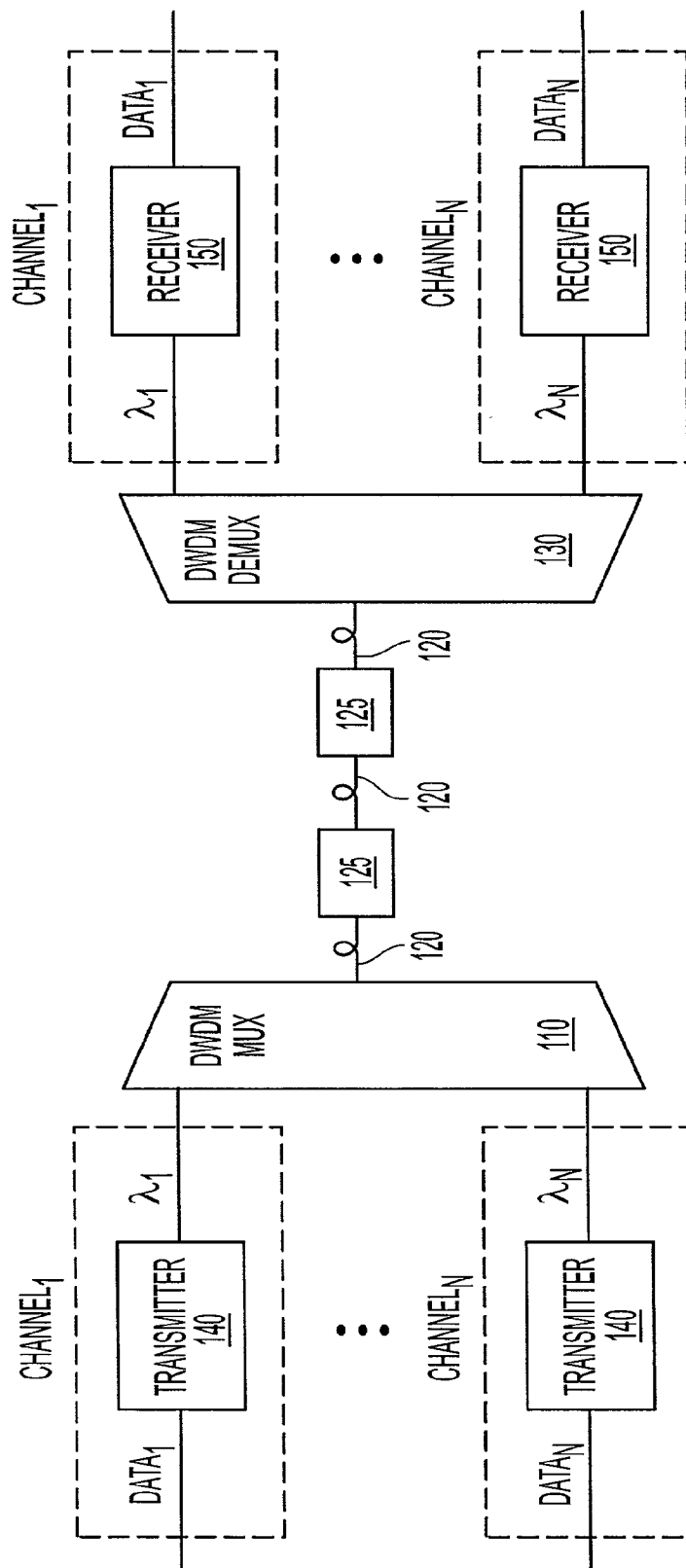


Fig. 1
(Prior Art)

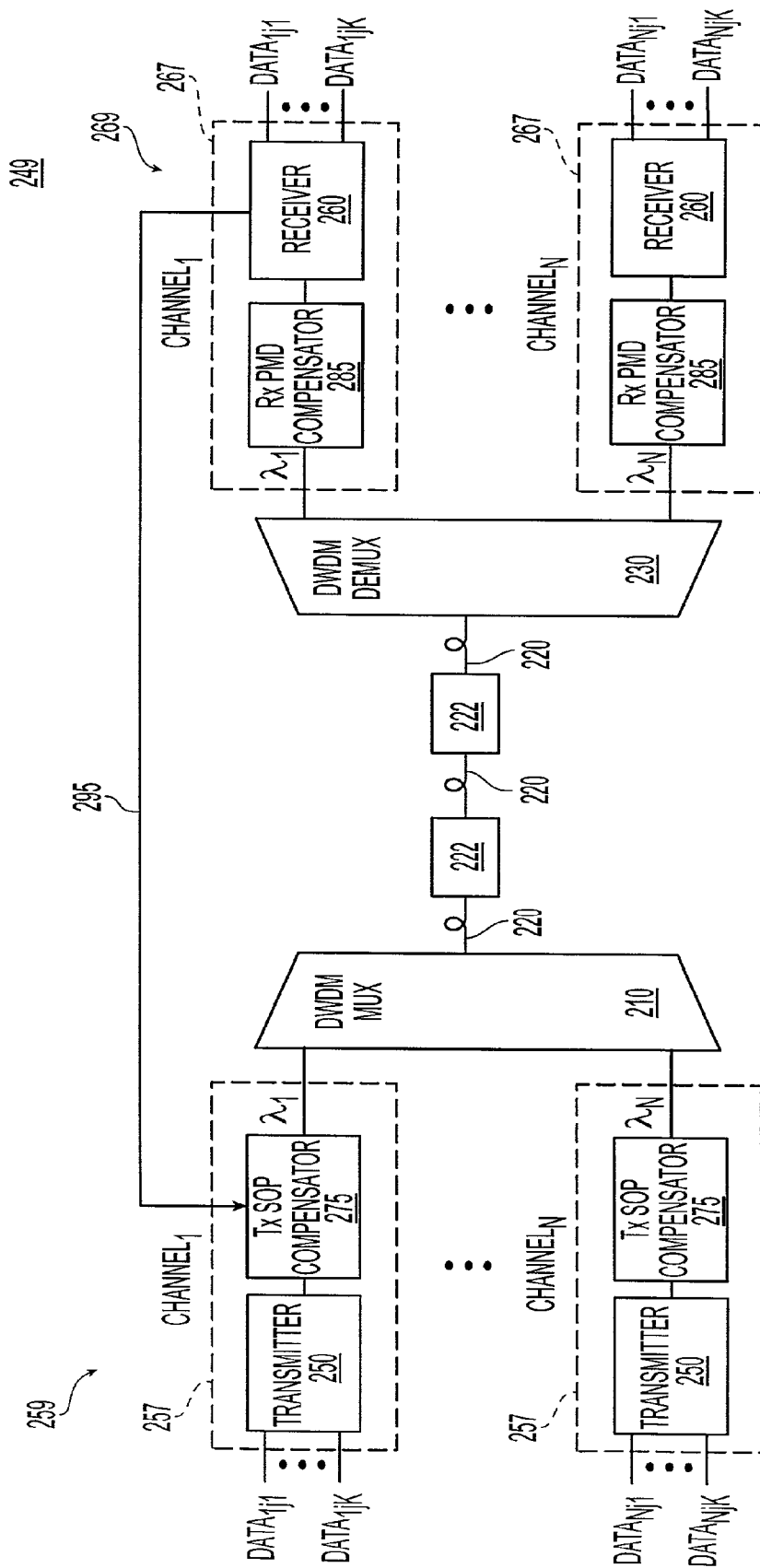
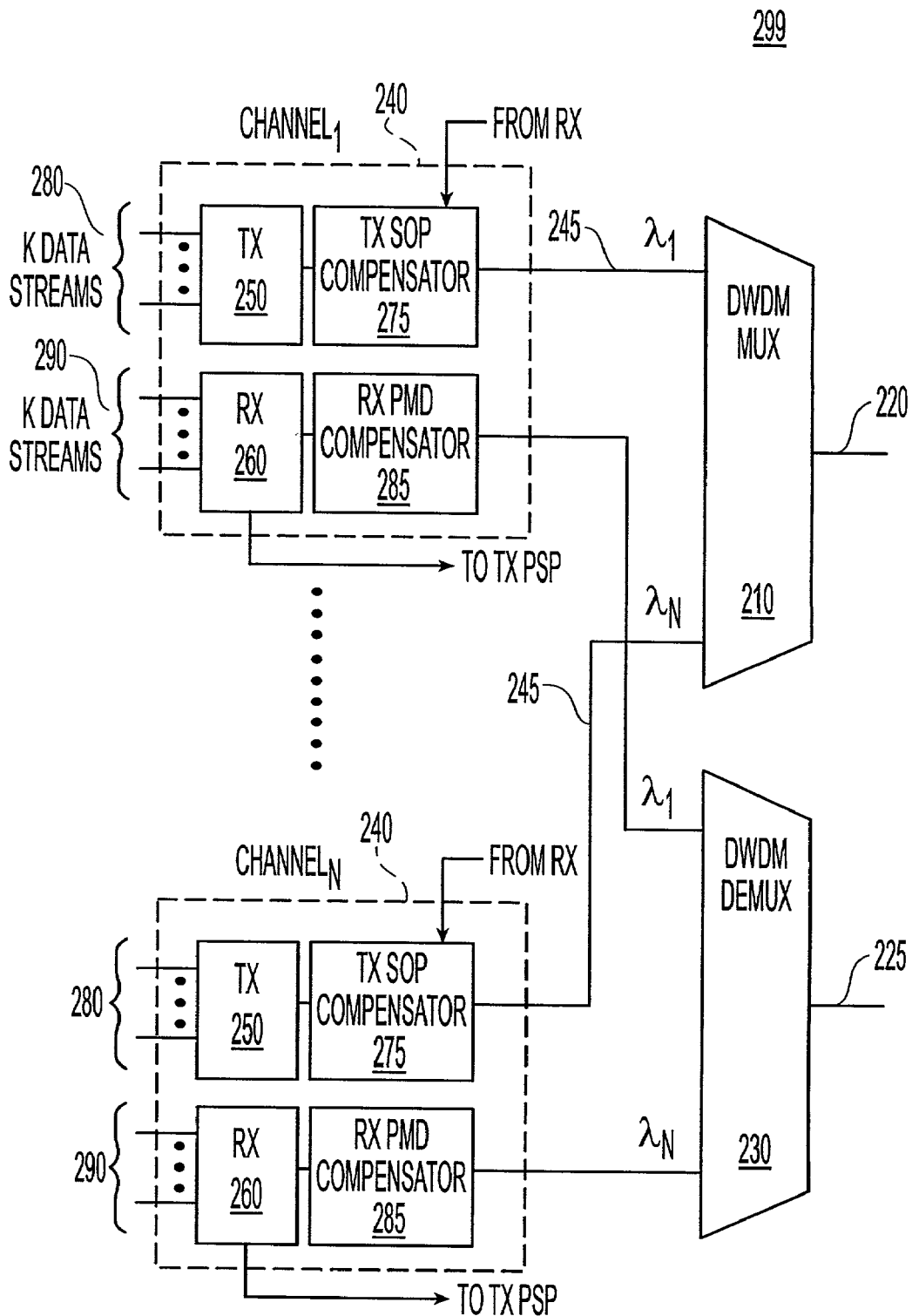


Fig. 2a

*Fig. 2b*

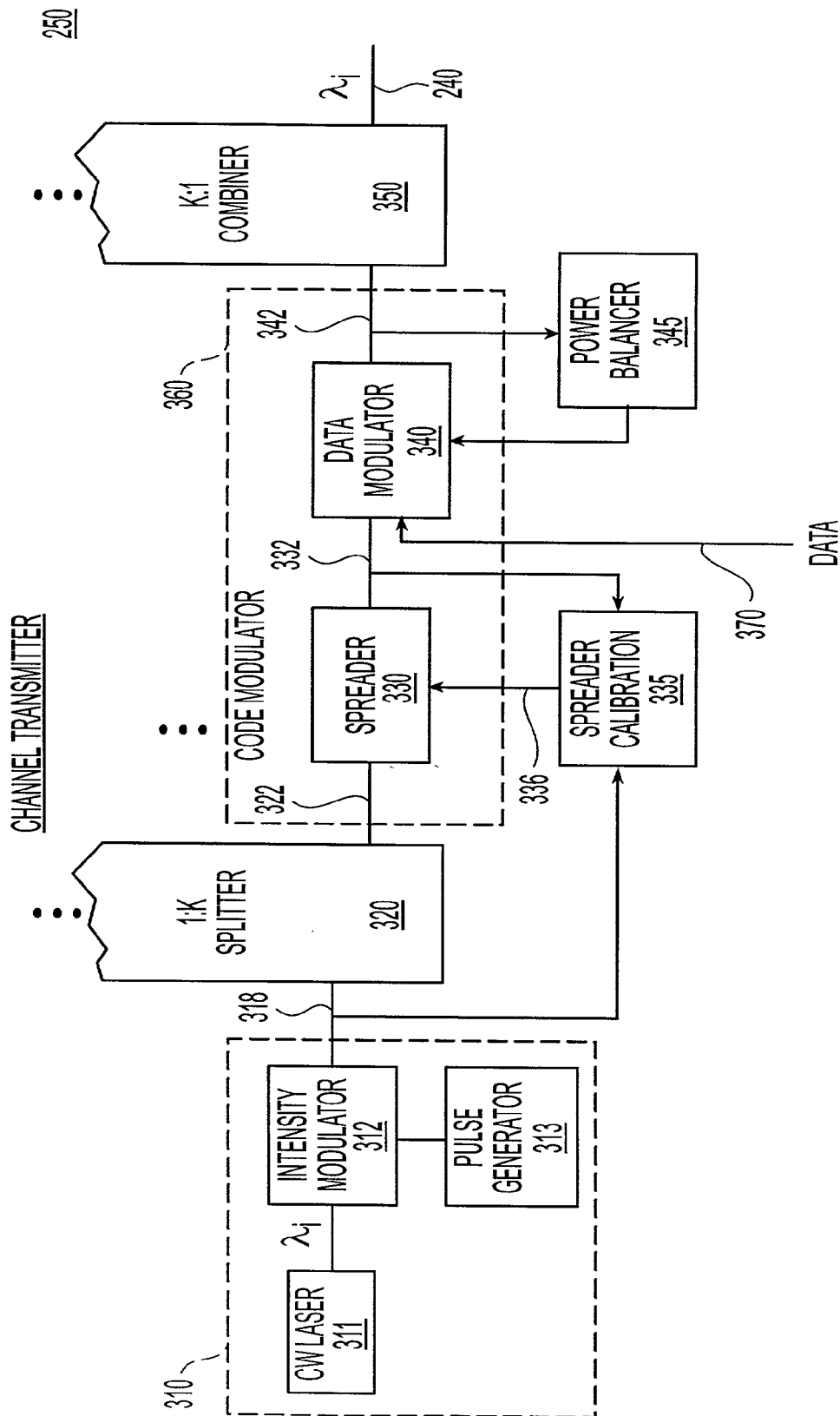


Fig. 3

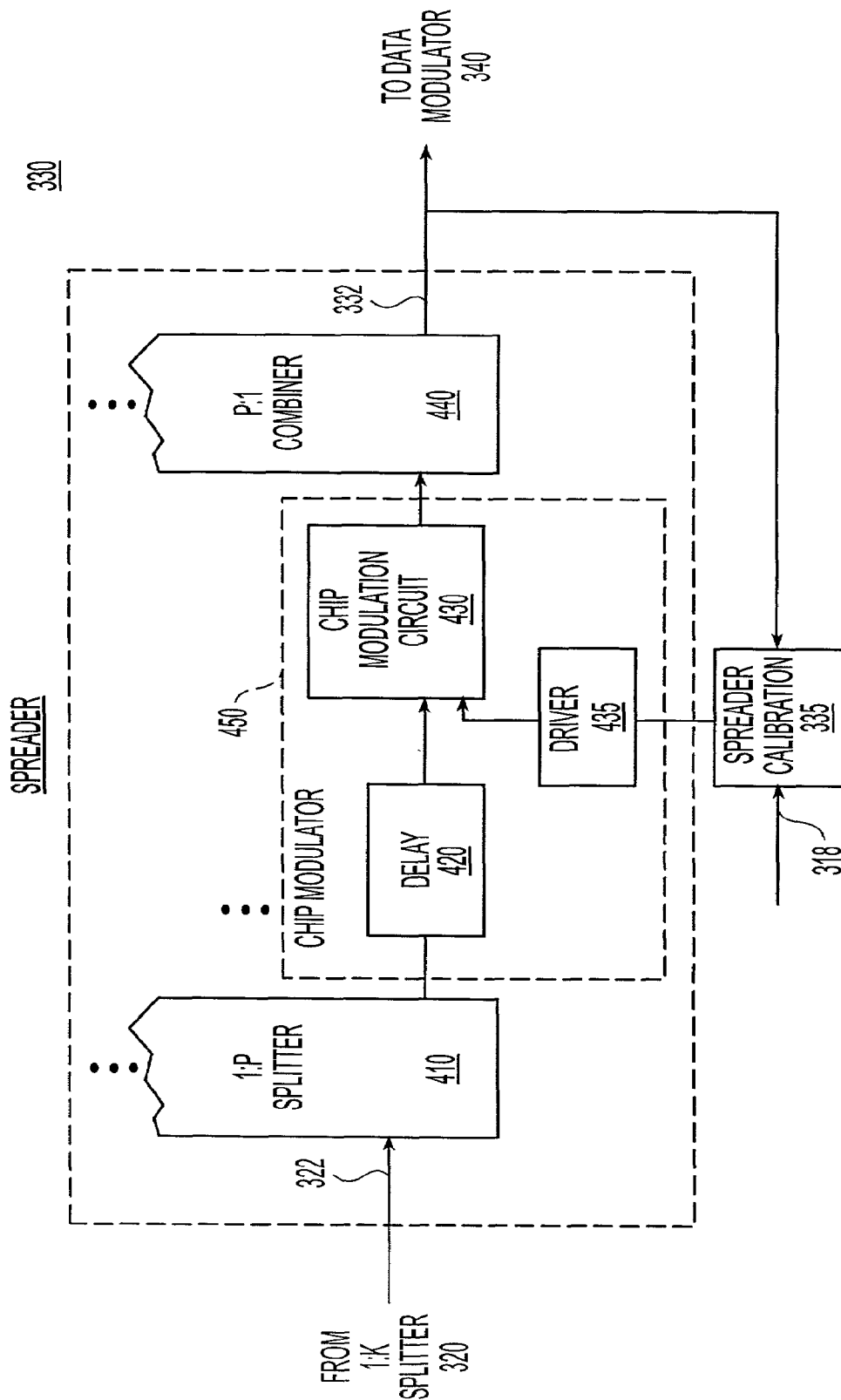


Fig. 4

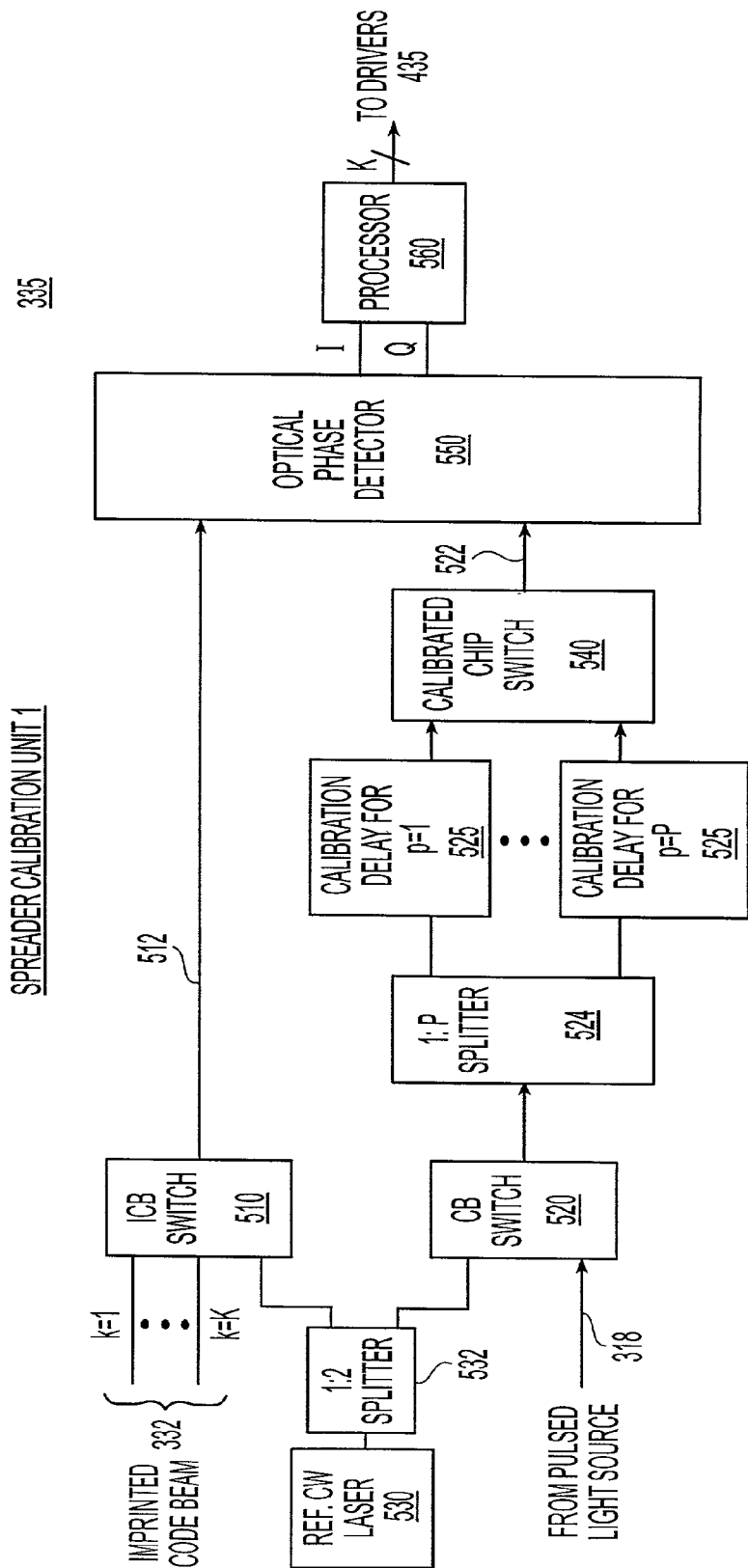


Fig. 5

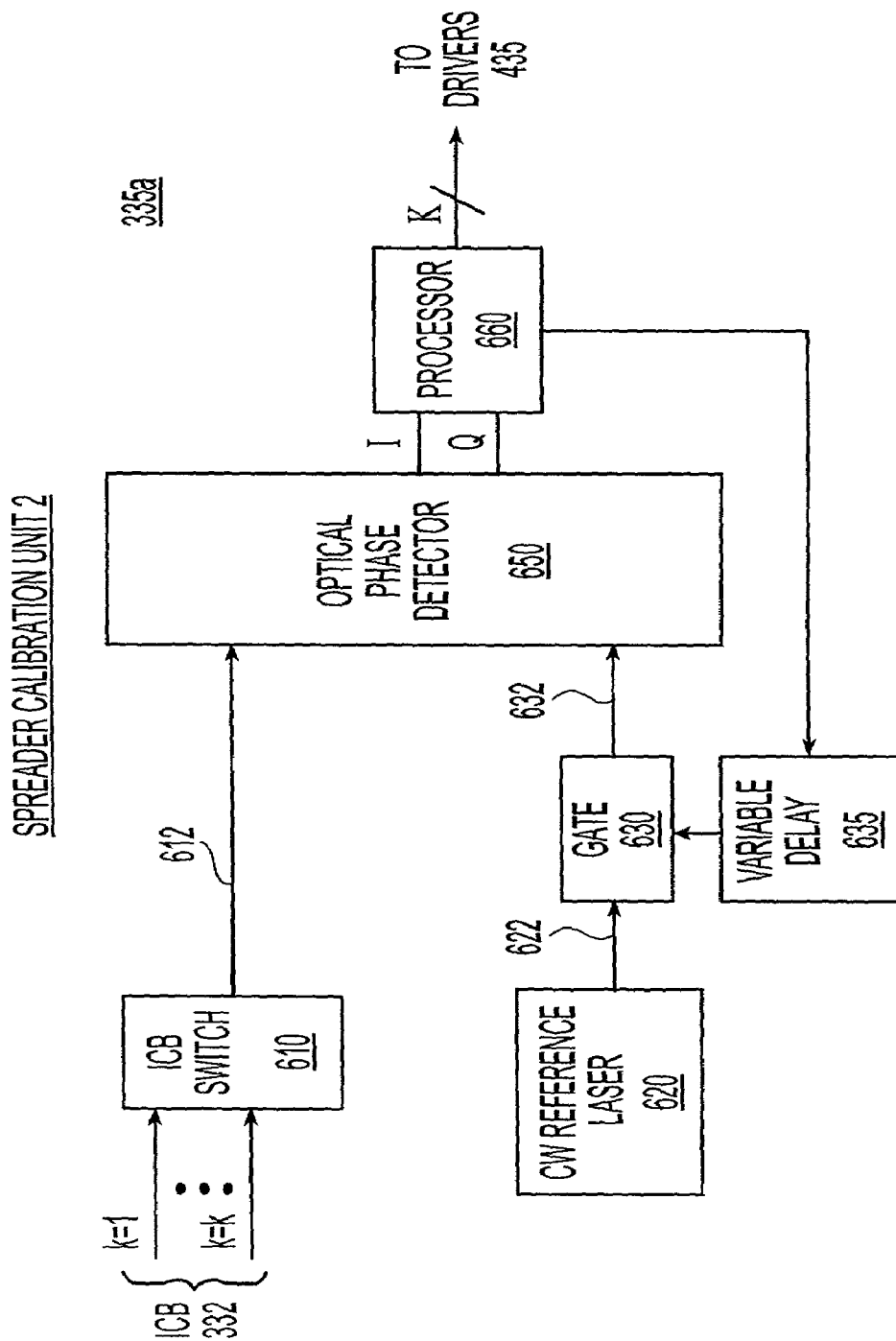


Fig. 6

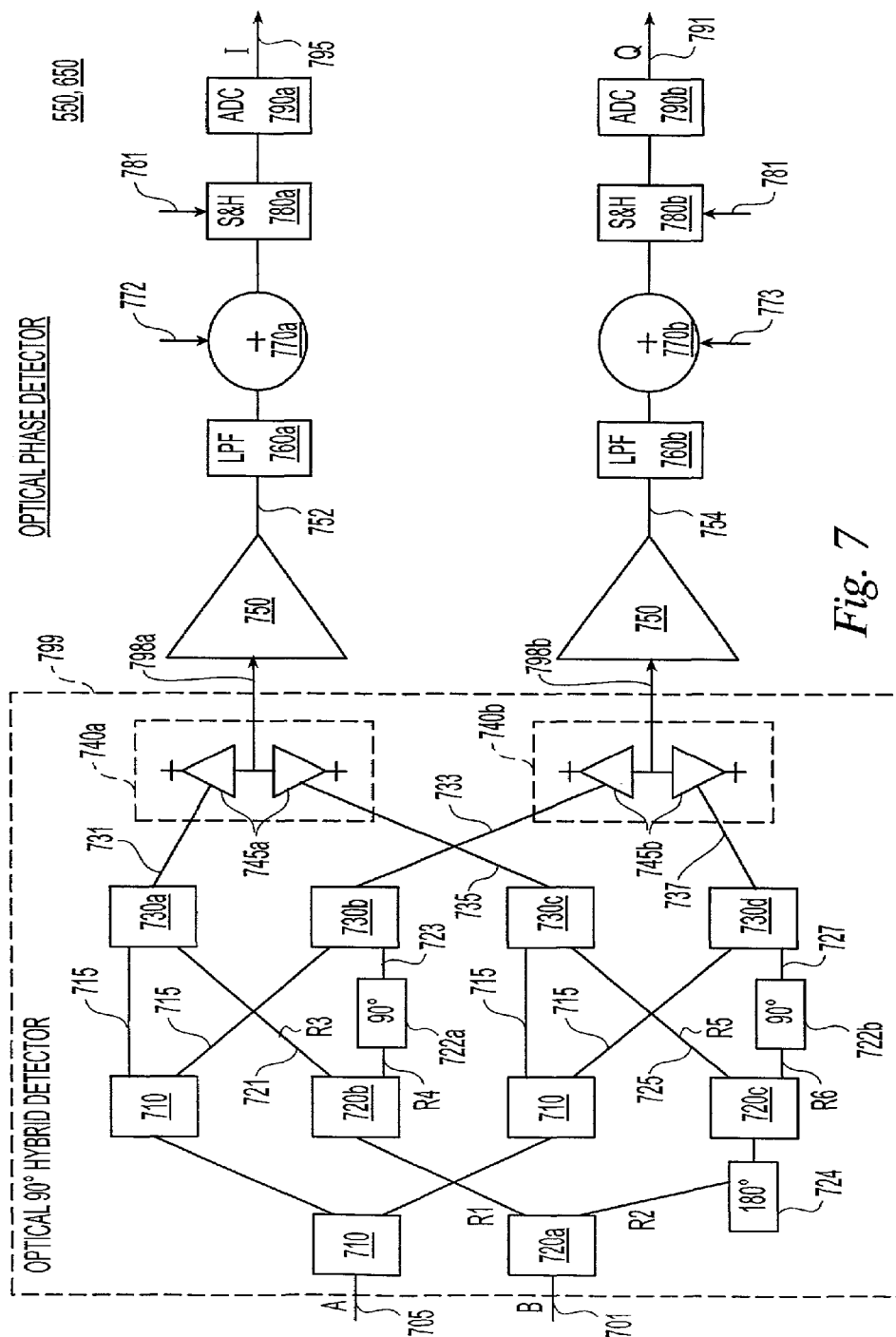


Fig. 7

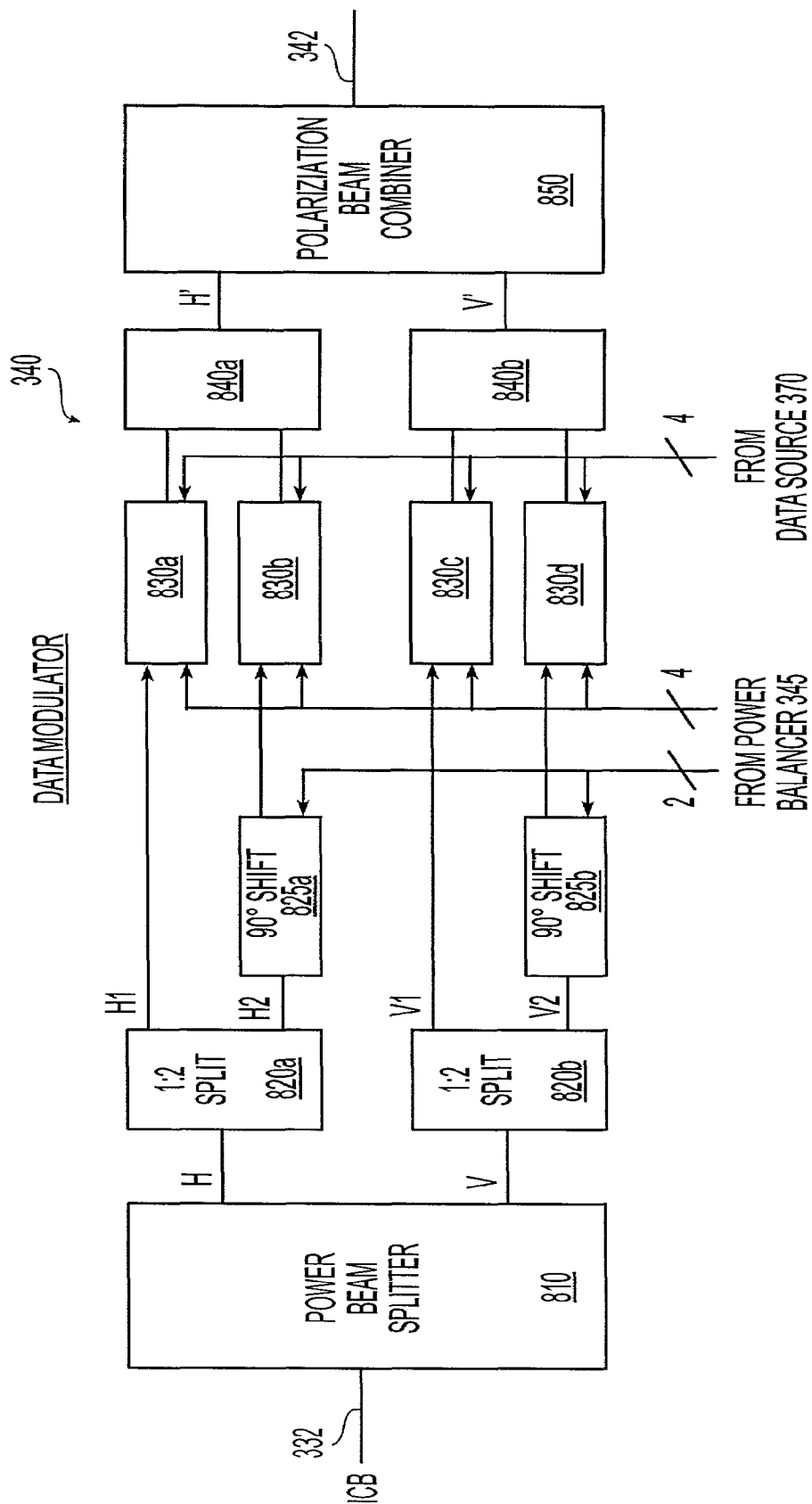
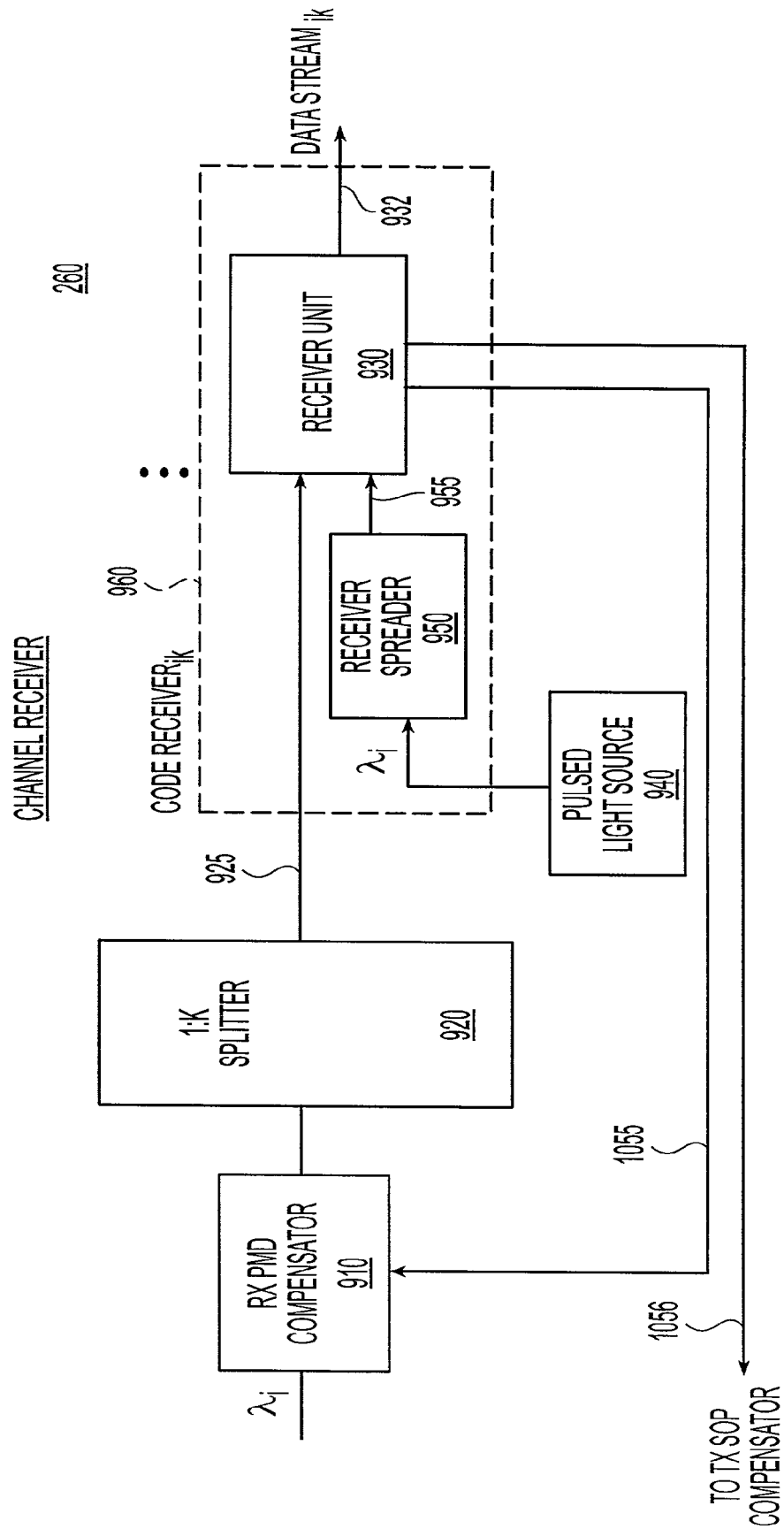


Fig. 8

*Fig. 9a*

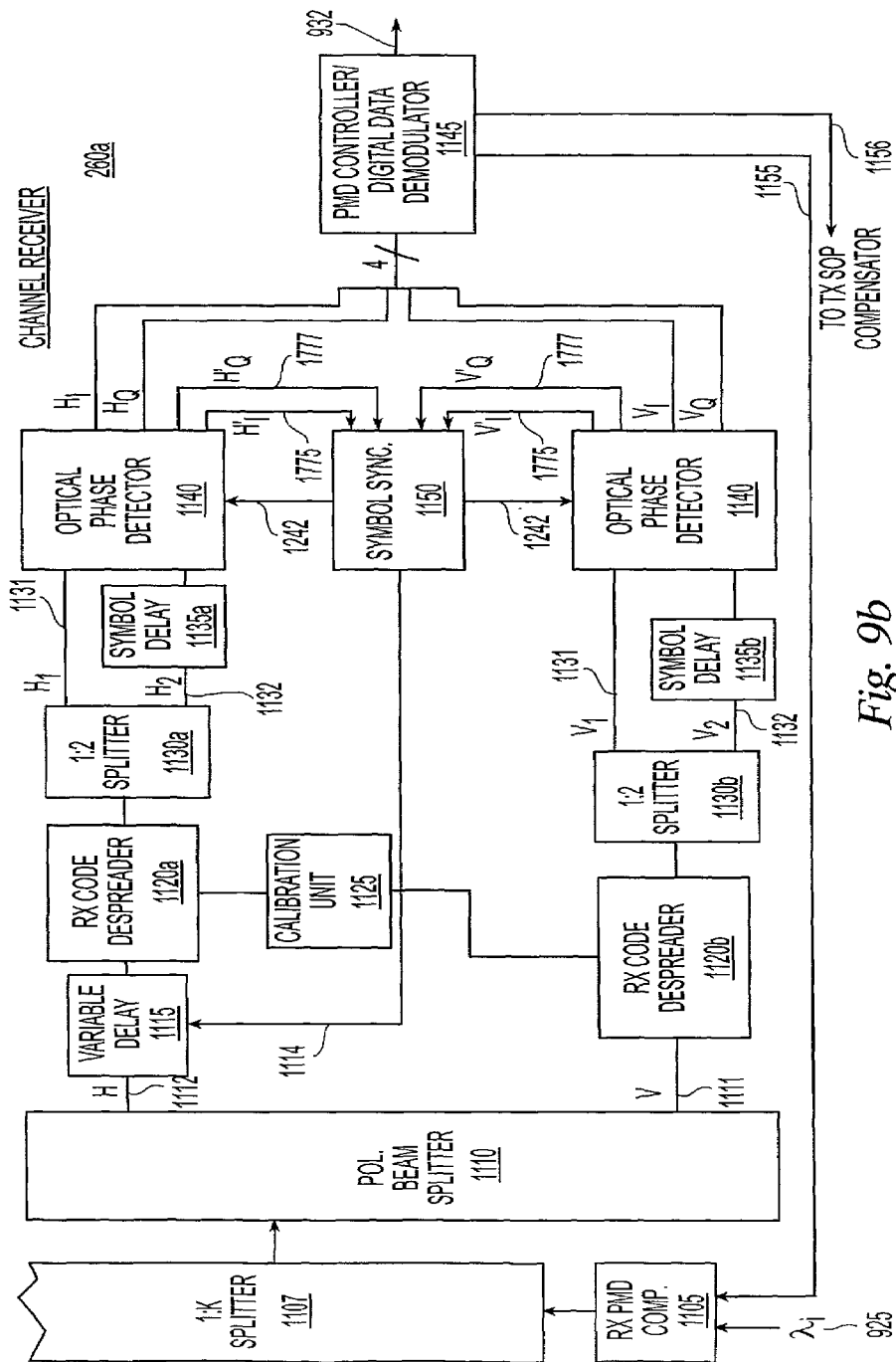


Fig. 9b

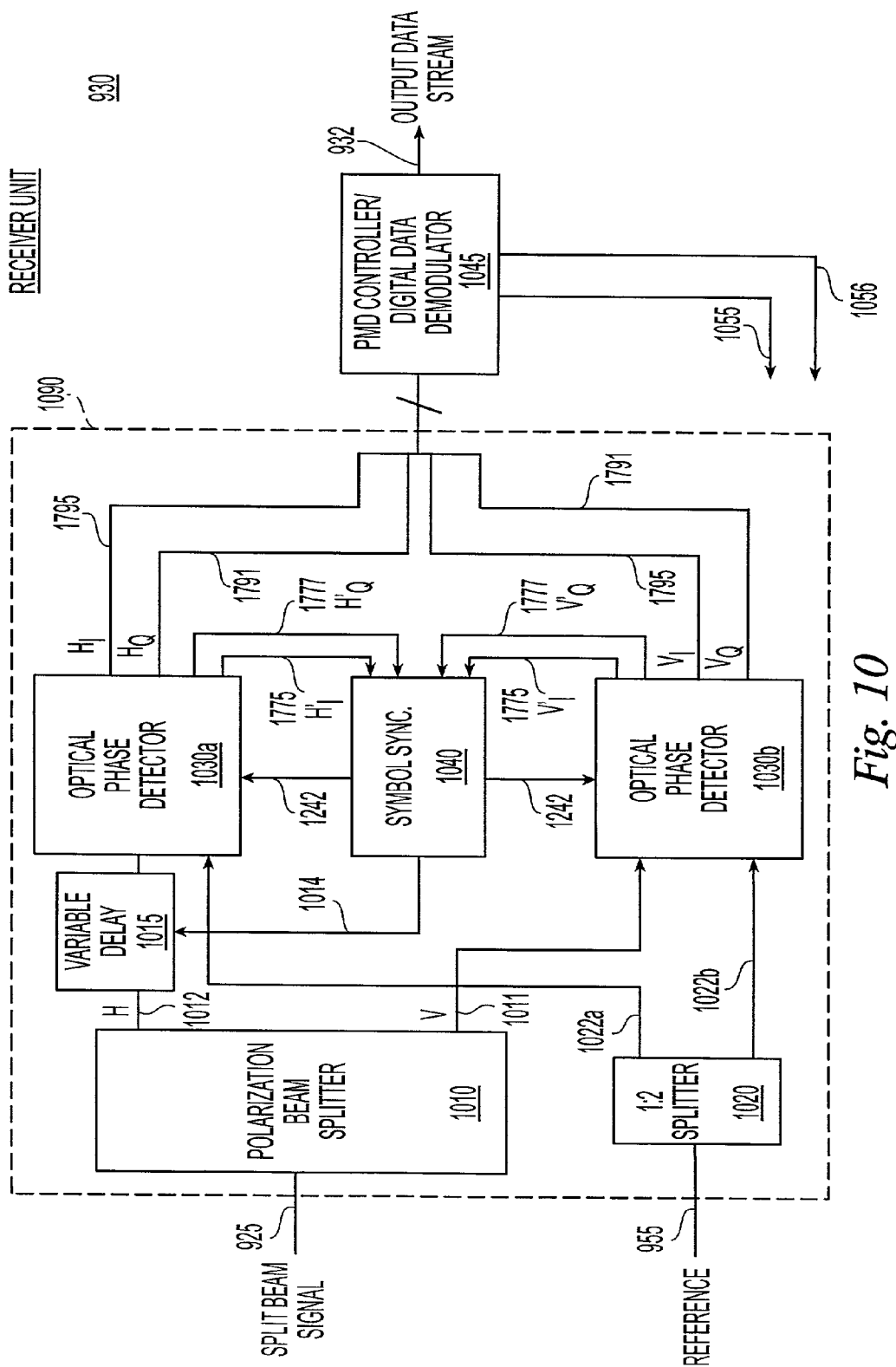


Fig. 10

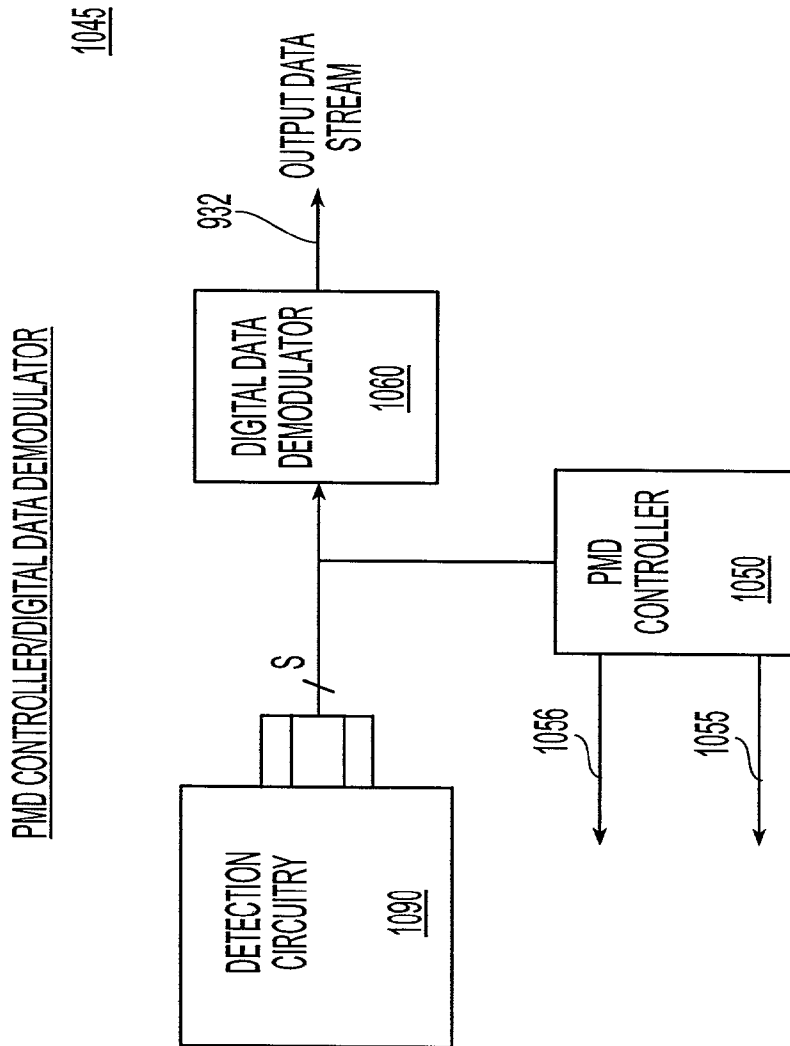


Fig. 10a

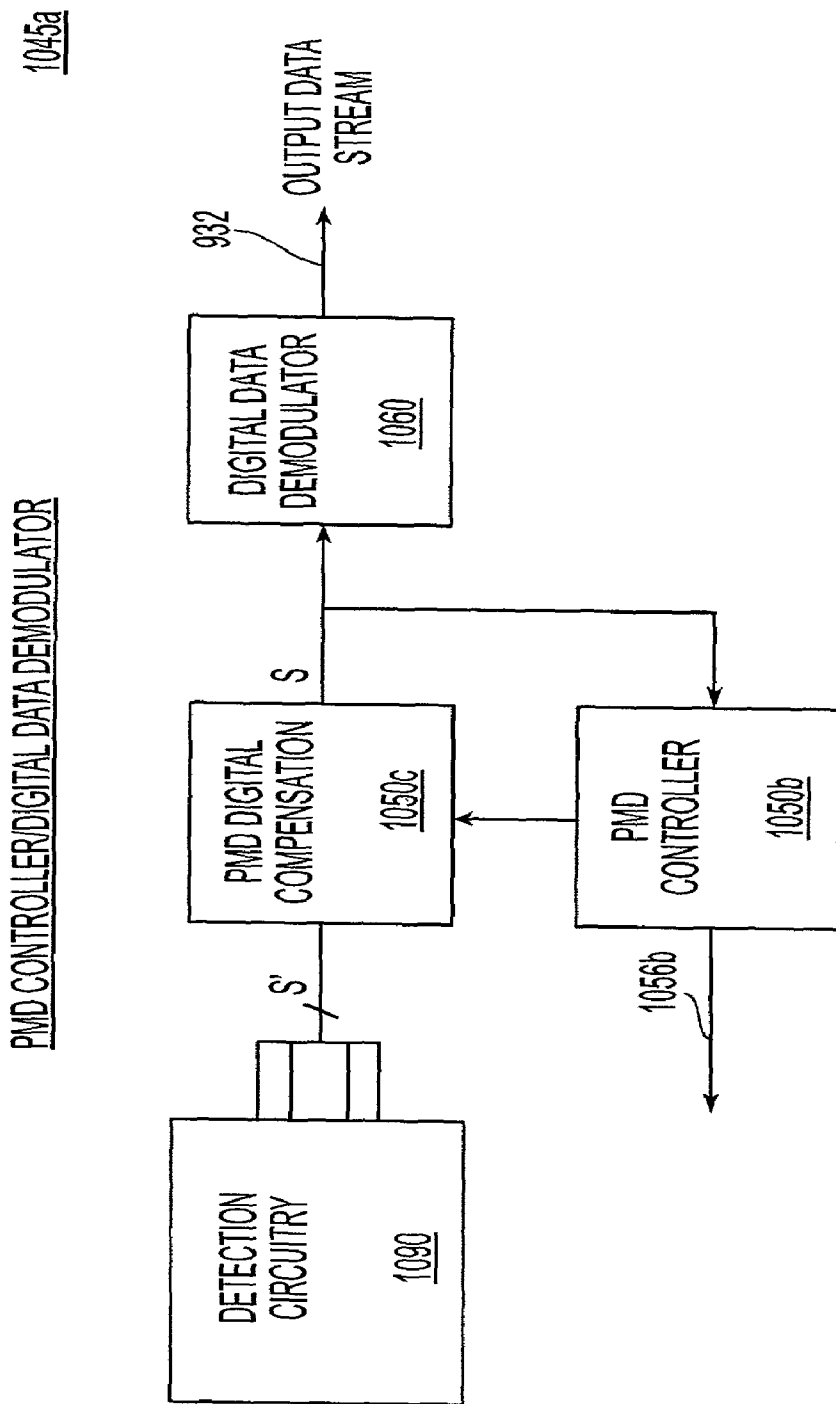


Fig. 10b

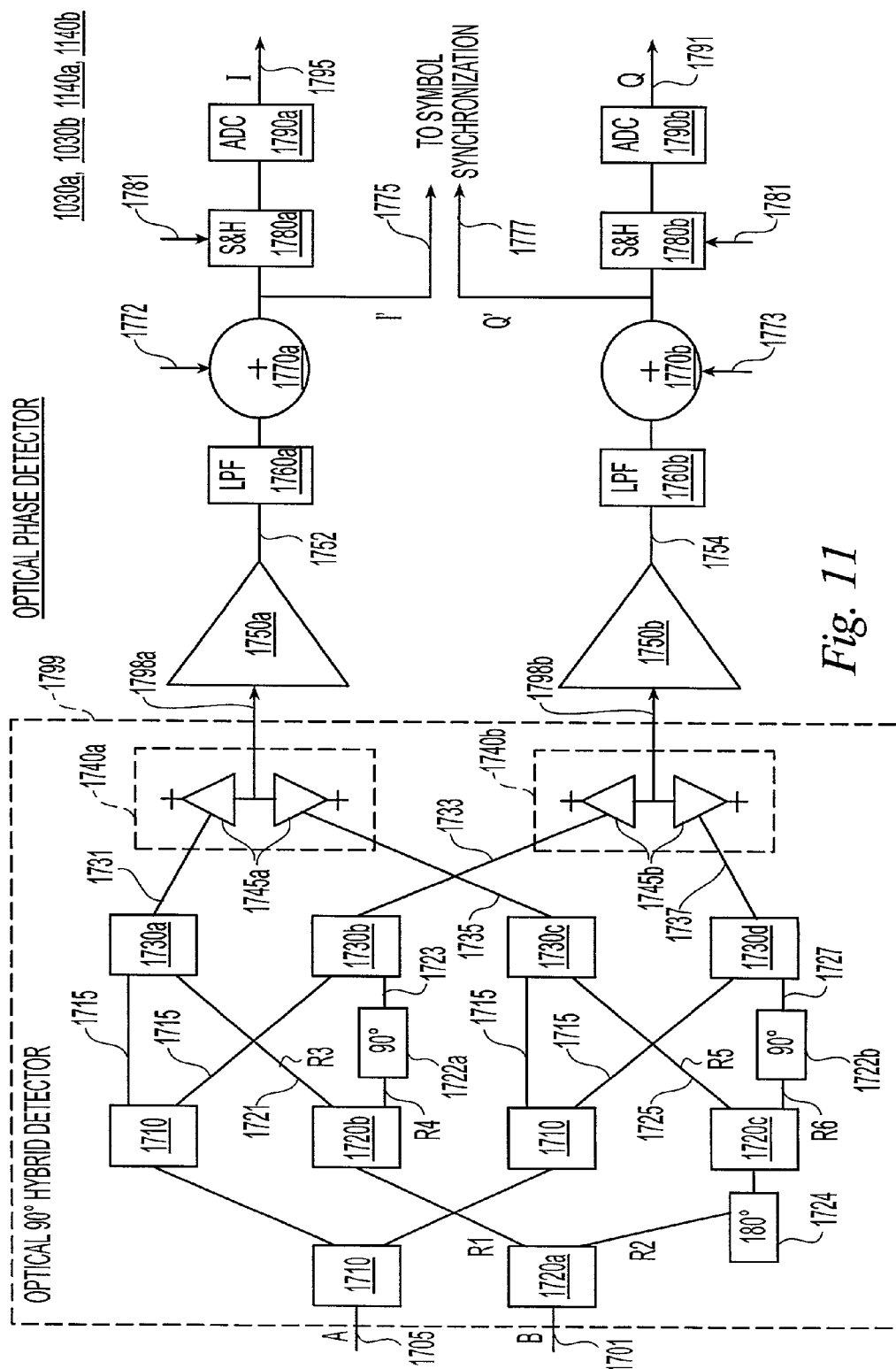


Fig. 11

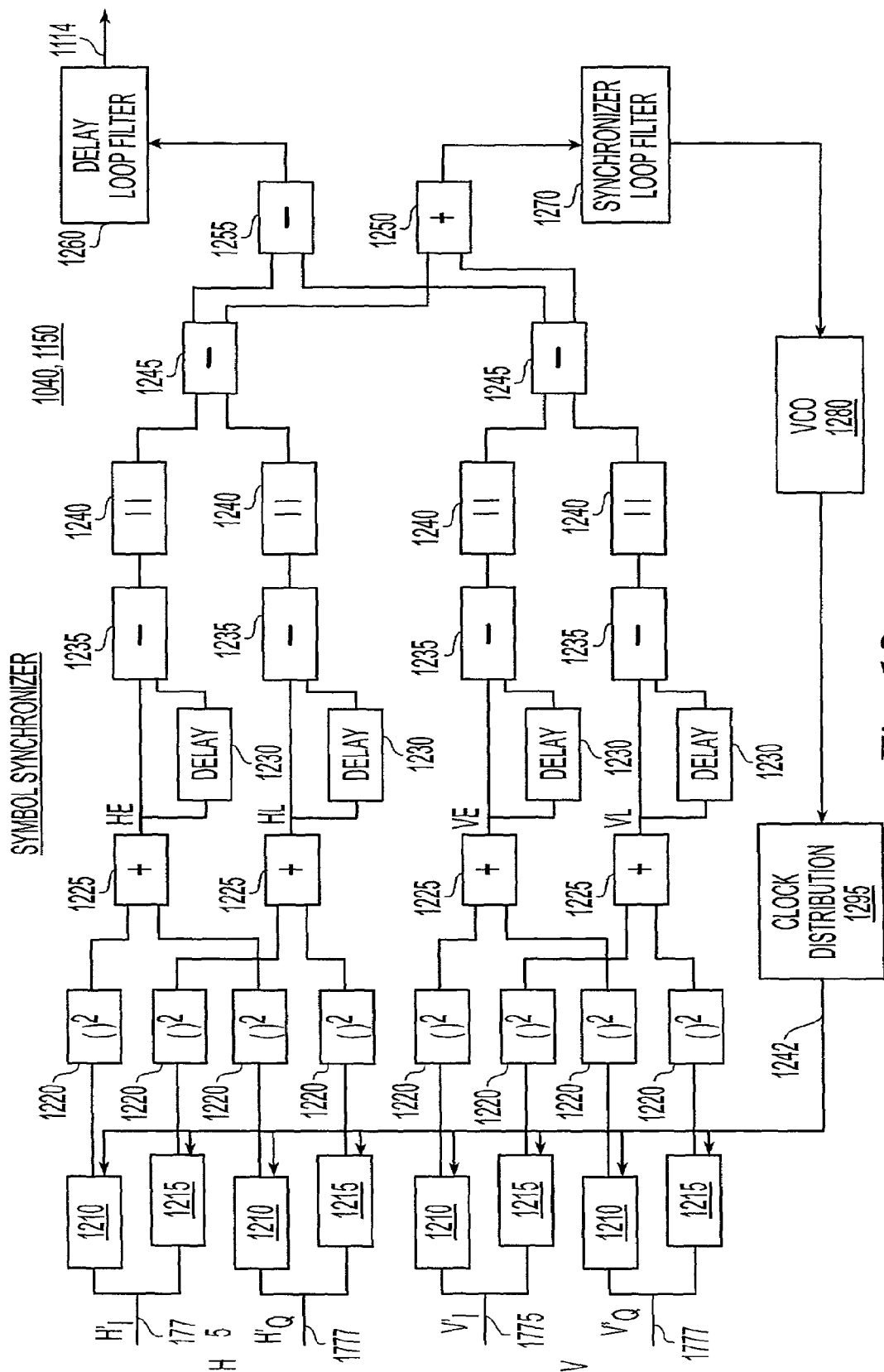


Fig. 12

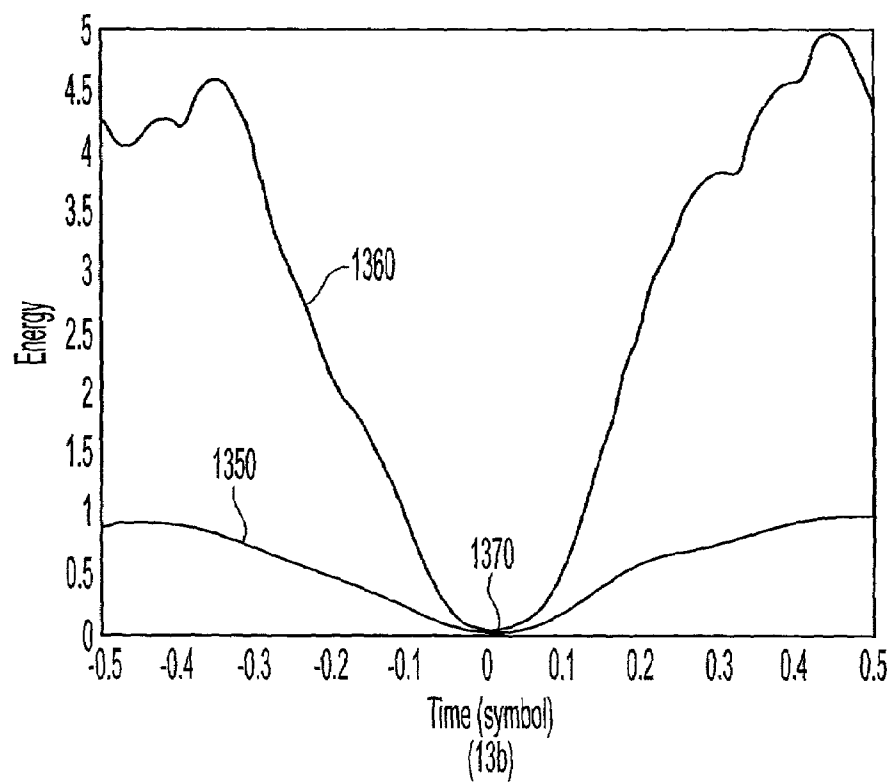
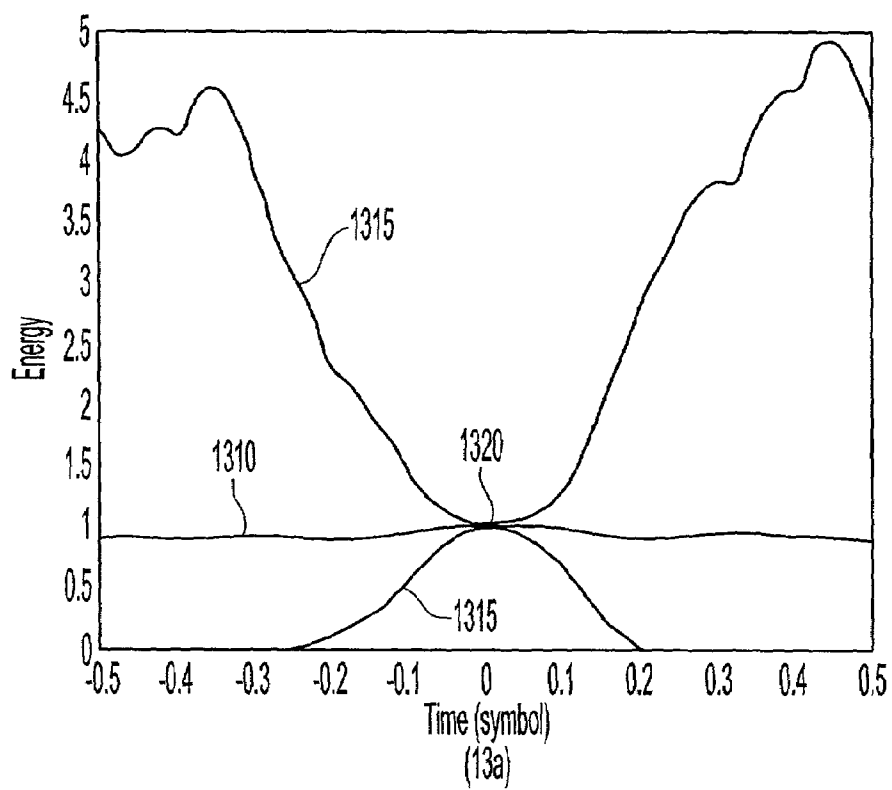
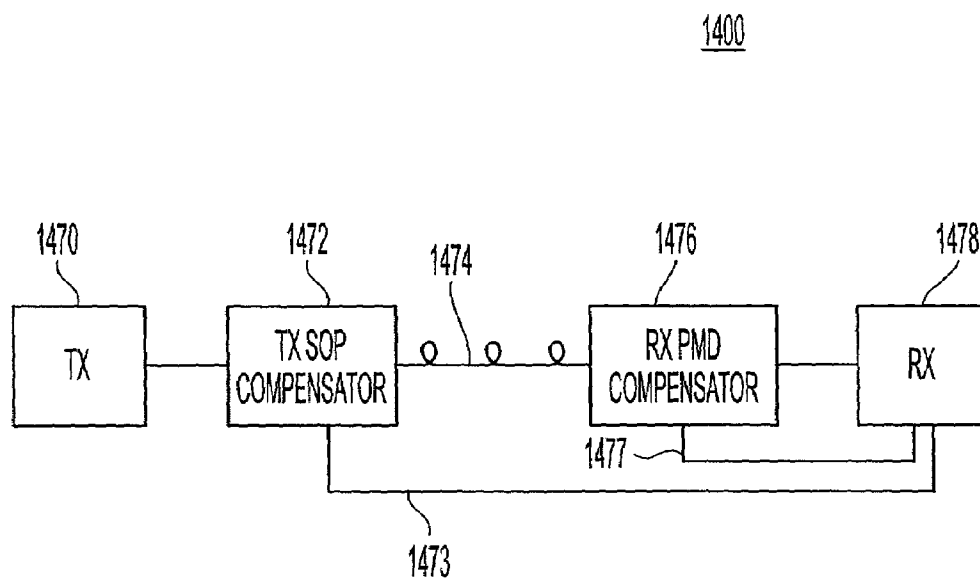
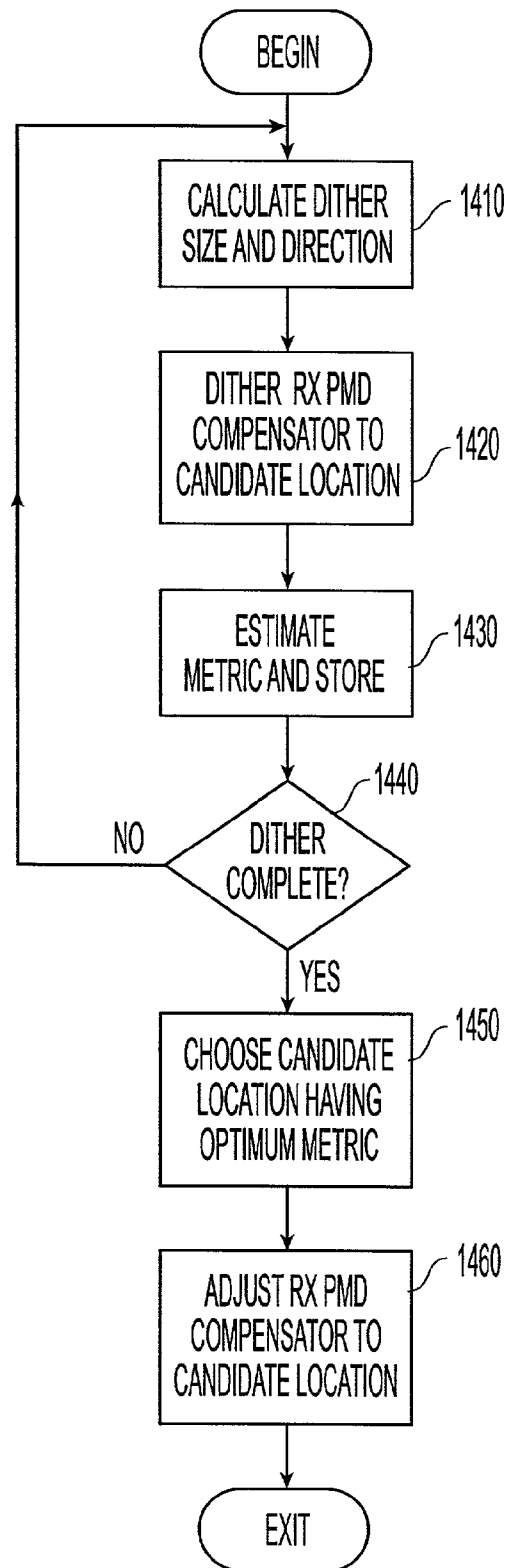
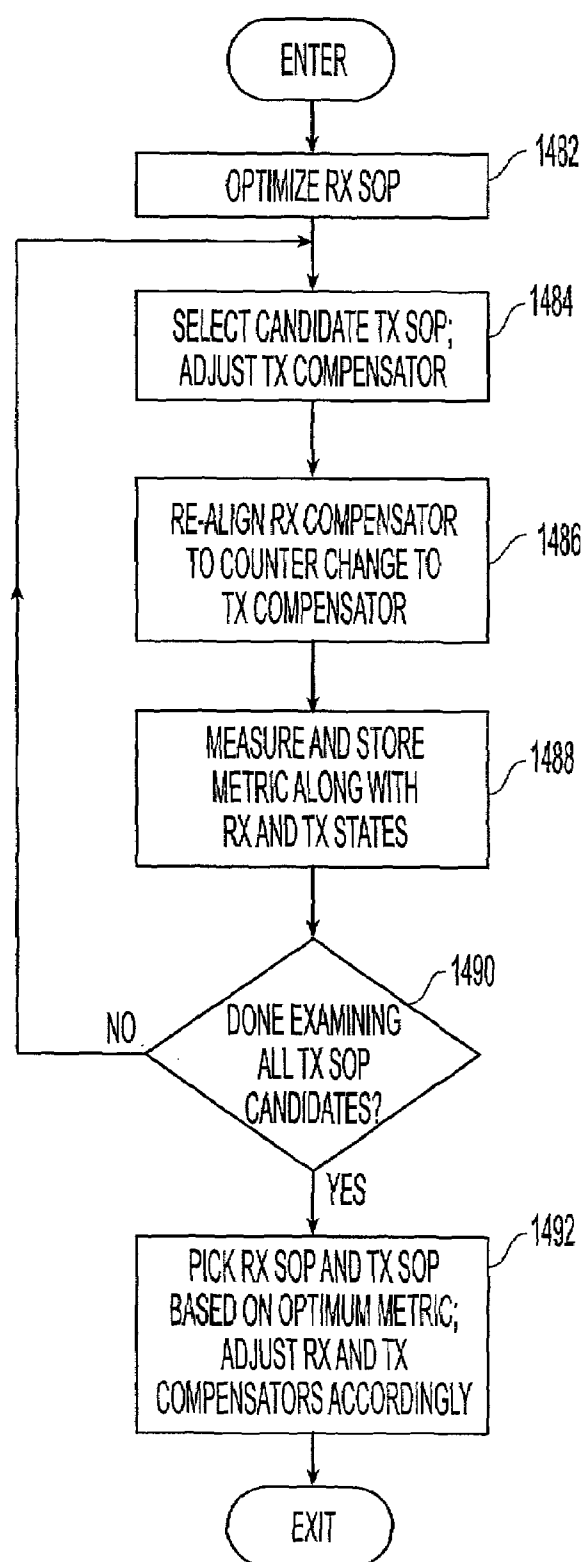


Fig. 13

*Fig. 14a*

*Fig. 14b*

*Fig. 14c*

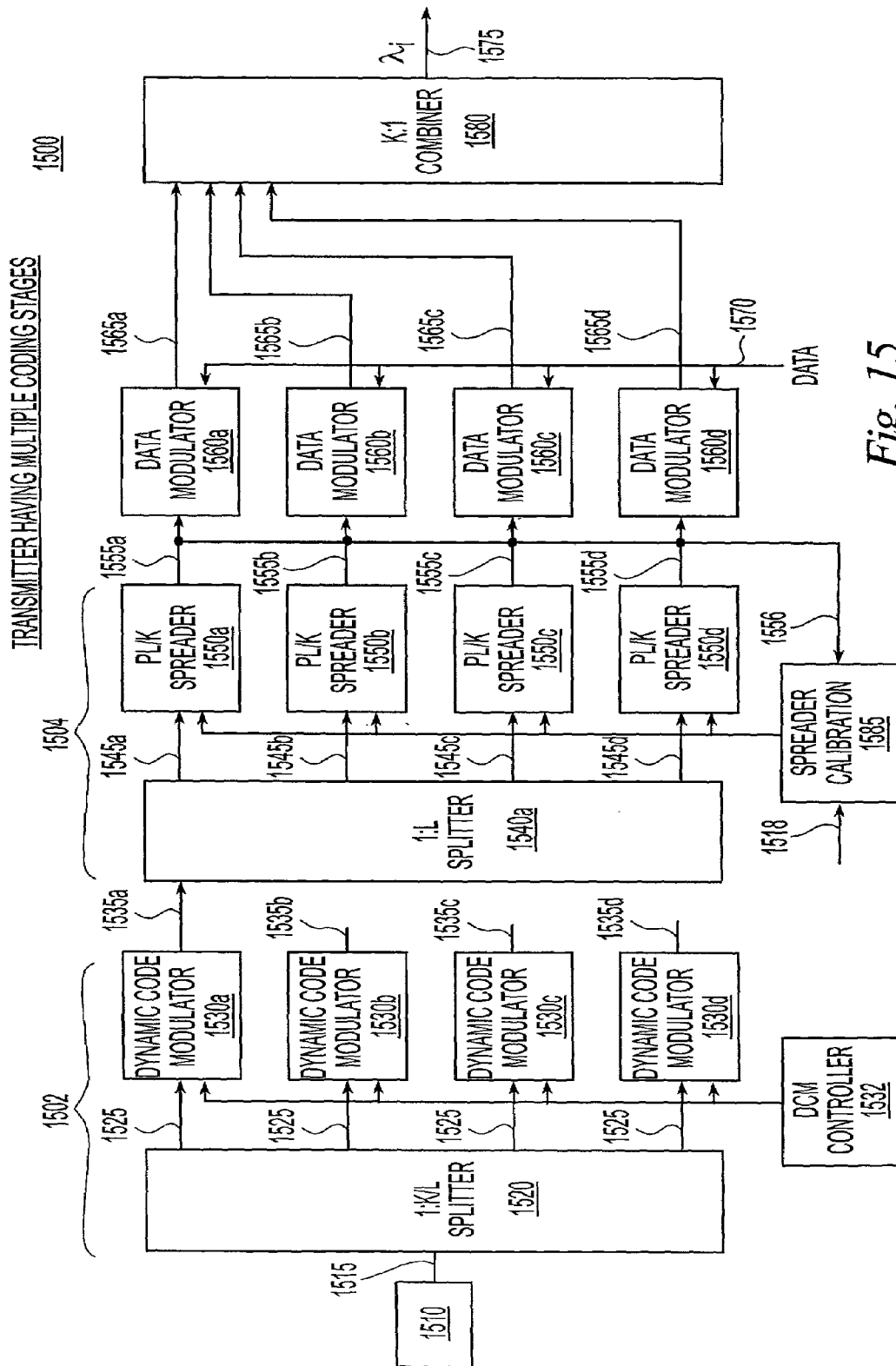


Fig. 15

1

SYSTEM AND METHOD FOR CODE DIVISION MULTIPLEXED OPTICAL COMMUNICATION

RELATED APPLICATIONS

The present application claims priority to U.S. Provisional application No. 60/234,930, filed Sep. 26, 2000.

FIELD OF THE INVENTION

The present invention relates to the field of optical communication systems utilizing modulation techniques to obtain high spectral efficiency.

BACKGROUND OF THE INVENTION

Dense wavelength division multiplexing (DWDM) increases the capacity of embedded fiber by assigning incoming optical signals to specific frequencies (wavelength, λ) within a designated frequency band and then multiplexing the resulting signals out onto one fiber. DWDM combines multiple optical signals so that they can be amplified as a group and transported over a single fiber to increase capacity of the telecommunication network. Each signal carried can be at a different rate (OC-3112/24, etc.) and in a different format (SONET, ATM, data, etc.). Limiting bandwidth of the useable band of the optical fiber to accommodate future growth is the driving force behind the effort to increase the spectral efficiency of DWDM systems.

FIG. 1 is a block diagram of a prior art simplex DWDM system. A DWDM multiplexer **110** combines several optical signals, hereinafter referred to as channels, into a single multi-channel optical signal that is transmitted through the optical fiber **120**. Optical amplifiers **125** may be connected to the optical fiber **120** to amplify the optical signal. Conversely, the DWDM demultiplexer **130** receives the multi-channel optical signal transmitted through the optical fiber **120** and splits it into separate channels. Each channel is characterized by a distinct wavelength designated as λ_i in FIG. 1 where the index, i , runs from 1 to N where N is the number of channels in the DWDM system. For an N -channel DWDM system, there are N transmitters **140** and N receivers **150** with one transmitter **140** and one receiver **150** for each channel. A transmitter **140** generates the optical carrier signal at the channel wavelength and modulates the carrier signal with a single data stream before transmitting the modulated optical signal to the multiplexer **110**. The multiplexer **110** then combines the N modulated optical signals having different channel wavelengths into a single multi-channel optical signal, and sends this through the fiber **120**. The demultiplexer **130** receives the multi-channel optical signal and separates it into the different channel wavelengths. Each receiver **150** then demodulates one of the demultiplexed channel signals to extract the data signal. While FIG. 1 shows a prior art simple system, it is understood that in real life, a duplex system is used, with one or more transmitters and receivers at each end. Dutton, Harry J. R., *Understanding Optical Communications*, 1998, pp. 513-568, ISBN 0-13-020141-3 presents a description of the DWDM system and of its components and is herein incorporated by reference.

The data rate (in bits per second or bps) through a single optical fiber may be increased by combining one or more of the following methods: increasing the data modulation rate;

2

increasing the number of channels per fiber; and selecting a modulation method having a higher spectral efficiency.

Increasing the data modulation rate is limited by semiconductor technology and cost, as well as frequency-dependent fiber impairments as chromatic and Polarization Mode Dispersion (PMD). Increasing the number of channels per fiber is limited by the properties of optical component materials. Current and proposed implementations of DWDM systems use a channel modulation rate of about 10 GHz (OC-192) and use 40 channels over the conventional optical band (C-band) between 1530 nm and 1560 nm. Therefore, the transmission bit-rate through a single optical fiber is about 400 Gbps. Each channel has a bandwidth of about 100 GHz. The spectral efficiency is defined as the channel bit-rate divided by the channel bandwidth. The spectral efficiency of the system is therefore 0.1 bit/Hz. The spectral efficiency may be doubled by using a coherent modulation technique such as quadrature phase shift keying (QPSK). QPSK encodes two bits per modulation period and therefore doubles the channel transmission bit-rate to 20 Gbps. The two bits encoded during QPSK are referred to as a symbol and the modulation period is referred to as the symbol period. The inverse of the symbol period is the symbol rate.

The channel bit-rate may also be doubled by combining two data streams into a single channel. U.S. Pat. No. 6,038,357 issued to Pan discloses a fiber optic network that combines two data streams into a single channel by polarizing the optical signal modulated by the first data stream to a polarization plane that is orthogonal to the polarization plane of the optical signal modulated by the second data stream.

Polarization mode dispersion (PMD) arises in optical fiber when circular symmetry is broken by the presence of an elliptical core or by noncircularly symmetric stresses. The loss of circular symmetry results in the difference in the group velocities associated with the two polarization modes of the fiber. The main effect of the PMD is the splitting of the narrow-band pulse into two orthogonally polarized pulses (dual imaging) that propagate through the fiber with the different group velocities. As the dual images propagate through the birefringent fiber, their states of polarization (SOP) constantly undergo changes causing the random coupling between the two images.

The PMD varies randomly from fiber to fiber. In the single fiber, the PMD also varies randomly with the optical carrier frequency and ambient temperature. PMD broadens and degrades the signal and limits the distance the signal may propagate before the information encoded in the signal is lost.

Therefore, there remains a need to improve the spectral efficiency of existing/planned DWDM standards (OC-48 at 2.048 Gbps or OC-192 at 10 Gbps) using existing fiber optic cables. There also remains a need for PMD compensation of the received optical signal.

SUMMARY OF THE INVENTION

In one aspect, the present invention is directed to an optical communication system having a transmitter configured to receive a first data stream and transmit a code division multiplexed optical signal comprising a number K code words modulated with first data from said data stream; and a receiver optically connected to the first transmitter and configured to receive said code division multiplexed optical signal, detect and demodulate said K code words within the code division multiplexed optical signal, and output said

3

first data, with the K code words being orthogonal to one another. The code words in said code division multiplexed optical signal include H and V polarizations.

In another aspect, the present invention is directed to a node in an optical communication system, the node having such a transmitter co-located with such a receiver.

In another aspect, the present invention is directed to a transmitter for a code division multiplexed optical communication system for sending K code words, each code having P pulses. In one embodiment, the transmitter has a pulsed light source, a transmitter splitter configured to output at least a number K identical code beams from the pulsed light source, a code modulator for each of the K identical code beams, each code modulator configured to receive one of the K identical code beams and output a corresponding data beam, and a transmitter combiner receiving and combining the K data beams to form a code division multiplexed optical signal comprising K data-modulated code words.

In another embodiment, the transmitter of the present invention has multiple coding stages, including a first coding stage which employs dynamic code modulators and a second coding stage that employs pulse spreaders.

In another aspect, the present invention is directed to a code modulator for use in an optical transmitter. The code modulator includes a pulse spreader and a data modulator. The pulse spreader includes a splitter which splits an incoming pulse into a plurality of P parallel pulses, P being the number of time chips in a code word, a time chip modulator to delay and code modulate each of the P pulses, and a P:1 combiner to create a single code word from the individually delayed and code modulated pulses.

In another aspect, the present invention is directed to a pulse spreader circuit configured to receive a single pulse within a predetermined time window and output an imprinted code beam having a number P modulated pulses within that time window. A spreader calibration unit receives the imprinted code beam from the pulse spreader and a reference light source as inputs, and outputs a spreader control signal which is sent to the pulse spreader.

In another aspect, the present invention is directed to a spreader calibration unit that ensures that each of the pulse spreaders has proper modulation by detecting and correcting an error in phase among a number P individual pulses belonging to one of a number K code words or pulse streams, each pulse occupying a chip period of length C.

In one embodiment, the optical pulse spreader calibration unit includes a first switch configured to select one from among (a) said K pulse streams, and (b) a reference signal, to thereby output a first signal; a second switch configured to select one from among (a) a pulsed light source having a pulse period of $P \cdot C$ and (b) to thereby output a second signal; a number P calibration delays each receiving the second signal as an input, the p-th calibration delay outputting a p-th delayed version of the second signal delayed by $(p-1) \cdot C$; a third switch receiving and combining P delayed versions of the second signal from P corresponding calibration delays to thereby output a third signal; and an optical phase detector configured to receive the first and third signals and output in-phase and quadrature signals derived from the first and third signals.

In another embodiment, the optical pulse spreader calibration unit includes a first switch configured to select one of the K encoded pulse streams and output a first signal; a phase detector having said first signal input thereto; a light beam directed into the phase detector via a gate during a selected chip period determined by variable electronic delay; wherein the phase detector determines an amplitude product

4

of, and a phase difference between, the first signal and the gated light beam; and the amplitude product and phase difference are passed to a processor that determines an offset that should be applied to correct an error in phase or amplitude of a pulse; and the processor outputs a signal to control the variable electronic delay.

In another aspect, the present invention is directed to an optical signal data modulator for use in a code modulator of the present invention. The optical signal data modulator is configured to receive a number P time chips of a code word belonging to a family of orthogonal codes, and modulate the orthogonal code words with data. The data modulator includes a power splitter which splits the incoming pulses into H and V components, a pair of power splitters to power split each component into H1 and H2 and V1 and V2 sub-components, respectively, a pair of phase shifters to phase shift the H2 and V2 sub-components by 90 degrees from H1 and V1 accordingly, four bit-modulators to then modulate each sub-component, a pair of first combiners to combine the two modulated H components to form a data modulated H' component and a data modulated V' component, and a polarization beam combiner which combines the data modulated H' and V' components into two orthogonal polarizations.

In another aspect, the present invention is directed to a receiver having a receiver splitter configured to split a received information signal comprising K orthogonal data-modulated code words into K identical received information signals, and K code receivers, each code receiver having a receiver pulse spreader configured to create a reference signal which corresponds to one of the K orthogonal data-modulated code words, and a receiver unit having the received information signal and the reference signal input thereto, wherein the receiver unit is configured to detect and demodulate that one of the K data-modulated code words to which the reference signal corresponds.

In another aspect, the present invention is directed to an optical detection circuit for use in a receiver unit in accordance with the present invention. The optical detection circuit receives the information signal and the reference signal, and outputs in-phase and quadrature components of first and second orthogonal polarization components of the information signal. The optical detection circuit includes a polarization beam splitter which splits the information signal into first and second orthogonal polarization components, a first optical phase detector that receives the first orthogonal polarization component and a reference signal as inputs, and outputs in-phase and quadrature components of the first orthogonal polarization component, a second optical phase detector which receives the second orthogonal polarization component and the same reference signal as inputs, and outputs in-phase and quadrature components of the second orthogonal polarization component, and a symbol synchronizer circuit that receives the in-phase and quadrature components of the first and second orthogonal polarization components of the information signal, and outputs at least one timing signal to synchronize symbol boundaries of said data-modulated codewords in said optical phase detectors.

A polarization mode dispersion controller associated with the receiver receives digitized in-phase and quadrature components of the first and second orthogonal polarization components of the information signal, and outputs at least one polarization control signal in response thereto.

In another aspect, the present invention is directed to an optical phase detector comprising an optical hybrid detector having first and second signal inputs and first and second signal outputs, the first signal output being proportional an

5

in-phase difference between the first and second signal inputs, and the second signal output being proportional to a quadrature difference between the first and second signal inputs; a first signal conditioning cascade circuit arranged to process the first signal output from the optical hybrid detector to thereby form a digitized in-phase component signal; and a second signal conditioning cascade circuit arranged to process the second signal output from the optical hybrid detector to thereby form a digitized quadrature component signal.

In another aspect, the present invention is directed to an optical hybrid detector having first and second signal inputs, and first and second signal outputs. The optical hybrid detector includes splitters, phase shifters and combiners to form the complex conjugate components of the first and second signal inputs. These components are input to a pair of matched detectors that output the in-phase and quadrature differences between the first and second signal inputs.

In another aspect, the present invention is directed to a symbol synchronizer for synchronizing symbols of a selected data signal from a multiplexed data signal. The symbol synchronizer uses the symbol-to-symbol energy difference, instead of finding the maximum energy.

In another aspect, the present invention is directed to a self-homodyne receiver. The self-homodyne receiver has a polarizing beam splitter to split an incoming optical code division multiplexed signal having K orthogonal code words modulated with data into first and second orthogonal polarizations. The receiver has K sets of first and second code despreaders. The k-th set of the first and second despreaders is configured to output first and second phase information, respectively, of data modulated on the k-th code word having first and second orthogonal polarizations, respectively. First and second optical phase detectors compare the first/second phase information from a current symbol with the first/second phase information from an immediately preceding symbol, and output first/second signals reflective of the phase differences between data from the current and preceding symbols.

In another aspect, the present invention is directed to a PSP-based PMD compensator, to compensate for PMD caused by the fiber and its environment over a long distance run, without the use of a repeater. The receiver restores a transmitted signal's polarization by aligning the SOP of the received signal with the SOP of the signal launched into the fiber. The transmitter selects the optimal SOP to launch the optical signal into the fiber by aligning the SOP with the principal state of polarization (PSP) axes of the fiber. The SOP transmitted along the PSP axes exhibits the least frequency dependence that minimizes the coupling of the propagating signal. The polarization transformation in the fiber is a time-varying process; therefore, both the receiver PMD compensator and the transmitter SOP compensator must be able to track those changes. The receiver sends back the information to the transmitter via a separate channel to adjust the transmitter SOP compensator to re-align transmitted SOP with PSP.

In yet another aspect, the present invention is directed to a method for adjusting the receiver-end polarization compensation device, and method for adjusting a transmitter-end polarization compensation device.

BRIEF DESCRIPTION OF THE FIGURES

The present invention may be understood by reference to the following detailed description of the preferred embodi-

6

ment of the present invention, illustrative examples of specific embodiments of the invention and the appended figures in which:

FIG. 1 is a block diagram of a simplex prior art DWDM system architecture;

FIG. 2a is a block diagram of a simplex optical communication system in accordance with a preferred embodiment of the present invention;

FIG. 2b is a block diagram of one-half of a duplex optical communication system in accordance with a preferred embodiment of the present invention;

FIG. 3 is a block diagram of a transmitter in accordance with one embodiment of the present invention;

FIG. 4 is a block diagram of the pulse spreader used in the transmitter of FIG. 3;

FIG. 5 is a block diagram of a first embodiment of a spreader calibrator used with the spreader of FIG. 4;

FIG. 6 is a block diagram of a second embodiment of a spreader calibrator;

FIG. 7 is a block diagram of the transmitter-side optical phase detector in a preferred embodiment of the present invention;

FIG. 8 is a block diagram of the data modulator in a preferred embodiment of the present invention;

FIG. 9a is a block diagram of the channel receiver in accordance with one embodiment of the present invention;

FIG. 9b is a block diagram of the channel receiver in accordance with another embodiment of the present invention;

FIG. 10 is a block diagram of the data demodulator in a preferred embodiment of the present invention;

FIG. 10a depicts one configuration for a PMD compensator/digital data demodulator circuit;

FIG. 10b depicts a second configuration for a PMD compensator/digital data demodulator circuit;

FIG. 11 is a block diagram of the receiver-side optical phase detector in a preferred embodiment of the present invention;

FIG. 12 is a block diagram of the symbol synchronizer in a preferred embodiment of the present invention;

FIG. 13a is a graph of the average symbol energy as a function of the symbol time;

FIG. 13b is a plot of the average symbol-to-symbol energy difference as a function of the symbol time;

FIG. 14a is a block diagram of the transmitter-receiver link of the present invention;

FIG. 14b is a flow diagram of a PMD controller for compensating the receiver of FIG. 14a;

FIG. 14c is a flow diagram of a PMD controller for compensating the receiver and the transmitter of FIG. 14a; and

FIG. 15 is a block diagram of a transmitter having multiple coding stages.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 2a is a block diagram of the system architecture of a simplex communication system 249 in accordance with the present invention. The communication system 249 has a transmitter end 259 and a receiver end 269. The transmitter end 259 has N transmitter modules 257, each corresponding to one of N channels, each channel being characterized by a different wavelength, λ_i , where the index, i, runs from 1 to N. The receiver end has N corresponding receiver modules 267. As seen in FIG. 2a, each transmitter module 257 includes a transmitter 250 and preferably also incorporates

transmitter-end state of polarization (SOP) compensation **275** positioned between the transmitter and the multiplexer. One such transmitter-end SOP compensator is provided for each channel. Similarly, each receiver module **267** includes a receiver **260** and preferably also incorporates a receiver-end polarization mode distortion (PMD) compensation **285**. As seen in FIG. 2a, the receiver PMD compensation is positioned between the demultiplexer and each receiver, with one such compensator again being provided for each channel.

Each transmitter module **257** receives, for its channel, a total of K data streams, the data streams being depicted by $DATA_{ijk}$, where subscript 'i' is again the channel index, j is the polarization index (either 'H' or 'V') and subscript 'k' is the data stream index. For a given 'i' and 'k', the 'H' and 'V' data streams are preferably used to modulate the same code word on H and V polarizations. Thus, each code word, when transmitted, is used on both polarizations, and each polarization carries different data $DATA_{iHk}$ and $DATA_{iVk}$. Thus, since the index 'j' takes on only two possible values, one may consider the incoming data streams to effectively comprise 2K data streams, each having a first component that will ultimately be encoded and sent on H polarization and a second component that will ultimately be encoded and sent on V polarization.

While the above 'data stream' nomenclature may be expedient to illustrate the effects of coding in accordance with the present invention, it should be kept in mind that a single data stream may be formatted in any number of ways including the " $DATA_{ijk}$ " representation discussed above. What is important is that the incoming data preferably is used to modulate the same code word on both H and V polarizations, with a total of K code words being combined and transmitted on each channel. Each code word includes both the 'H' and 'V' data components, i.e., both 'j' values from a " $DATA_{ijk}$ " data stream and these are encoded in a single code word.

Each transmitter module **257** preferably encodes the K data streams using K codes created by its transmitter **250**, and preferably four bits are encoded on each code word. The encoded signal for each channel is sent to a multiplexer **210** which combines the encoded channels into a single encoded multi-channel optical signal. The encoded multi-channel optical signal is sent over an optical fiber **220** to a demultiplexer **230** which separates the encoded multi-channel optical signal into the various channel wavelengths. The individual channel wavelengths are then sent on a receiver module **267** corresponding to that channel. If desired, optical amplifiers **222** may be used, although this is not a requirement of the present invention. At the receiver module **267**, the received signal is received and demodulated by the receiver **260** which outputs the K data streams.

When compensation is provided for, the receiver circuitry **260** sends an auxiliary signal **295** to the transmitter-side SOP compensator **275**. This preferably is done out-of-band, on a continuous basis to mitigate polarization mode distortion caused by the fiber and the other optics.

FIG. 2b shows a node **299** representing one-half of a bidirectional fiber optic communication link in accordance with the present invention. The node **299** preferably accommodates a number N of channels **240**, each channel comprising a set including a transmitter **250** and a receiver **260** which are co-located. Indeed, the entire suite of all N channels preferably are placed at a single site or node.

Each end of the link has a DWDM multiplexer (Mux) **210** connected to the downstream optical fiber **220** and a DWDM demultiplexer (Demux) **230** connected to the upstream opti-

cal fiber **225**. The downstream fiber **220** is connected to the Demux at the other end of the link and the upstream fiber **225** is connected to the Mux at the other end of the link. In a preferred embodiment, the optical fibers **220** **225** are single mode fibers capable of transmitting optical signals in the C-band (wavelengths between 1530 nm and 1560 nm). The Mux **210** multiplexes N channels **240** for transmission through the fiber **220** and the Demux **230** demultiplexes the received optical signal from the fiber **220** into N channels **240**. For purposes of clarity, FIG. 2 shows only two channels **240** but it is understood that N channels are represented in FIG. 2.

Each channel **240** is characterized by a different wavelength, λ_i , where the index, i, runs from 1 to N. In a preferred embodiment, N is equal to 40 thereby giving each channel a bandwidth of about 100 GHz. Each channel **240** is capable of carrying K codes **280** and each code **280** carries a data stream. For each channel **240**, a transmitter (Tx) **250** creates the K codes, modulates each code **280** with a data stream, and combines the K data modulated codes into an optical channel signal **245** before passing the optical signal **245** to the multiplexer **210**. Each channel **240** also includes a receiver (Rx) **260** that recovers the K data streams from the Demux **230**.

In a preferred embodiment, K=16 codes are carried in each of the N=40 channels of the C-band at a symbol rate of 2.5 GHz with a symbol period of 400 ps, and 4 bits per symbol. This results in a capacity of 6.4 Tb/s and a spectral efficiency of 1.6 bits/Hz. Each code is further time sliced into 16 chips per symbol period for a chip period C=25 ps.

The detailed description of each component is now described. The Mux **210**, Demux **230**, optical fiber **220**, and fiber amplifier components **222** are known to one of skill in the optical communications art and need not be described further. Common devices such as splitters, combiners, phase shifters, optical switches, delay lines, intensity and phase modulators and CW lasers are also known to one of skill in the optical communication art and need not be described further. Similarly, one skilled in the art of digital signal processing is able to implement the functions of adders, subtractors, squaring and absolute value using a DSP chip and also designing amplifiers and other standard components without undue experimentation. Accordingly details of such implementations are not included herein.

Transmitter

FIG. 3 is a block diagram of a transmitter **250** configured to create a code division multiplexed signal in accordance one embodiment of the present invention. Coherent pulsed light source **310** generates a linearly polarized monochromatic light beam characterized by wavelength, λ_c . In a preferred embodiment, the coherent pulsed light source **310** comprises a continuous wave laser **311** that generates a coherent monochromatic light beam. The light beam is directed into an intensity modulator **312**. The intensity modulator **312** is, in turn, controlled by a pulse generator **313**. In a preferred embodiment, the pulse generator **313** and intensity modulator **312** produce an optical stream having a pulse period (time between pulses) of T=400 ps, which corresponds to a 2.5 GHz symbol frequency, and a pulse width between 10 ps and 20 ps. In another embodiment, the coherent light source **310** is a mode-locked laser that directly generates a similar pulse stream.

The pulsed light beam **318** is passed through a splitter **320** that splits the light beam **318** into K code beams **322**. Each code beam **322** is modified to produce K unique codes using a code modulator **360**. For purposes of clarity, FIG. 3 shows the modification of only one of the K code beams **322** and

it is understood that the remaining code beams are directed to structures identical to those designated as **360** in FIG. **3**. In a preferred embodiment, K is equal to 16 although any number of code beams **322** may be used and is within the scope of the present invention.

Each code beam **322** is passed through pulse spreader **330** wherein each code beam **322** is imprinted with a unique code comprising P pulses and having duration T. Each imprinted code beam **332** is then passed through a data modulator **340**. The data modulator **340** modulates the imprinted code beam **332** with a data stream **370** to produce a data beam **342**. Data beam **342** comprises two orthogonal polarizations, each modulated independently by the data, as discussed below with regard to the data modulator **340**. Each data beam **342** is then combined with the other data beams having wavelength λ_i in a combiner **350** to form a channel beam. The channel beam output by the transmitter is thus a code division multiplexed optical signal comprising K data-modulated code words which are sent on the channel **240**. A single channel **240** is therefore capable of carrying K data streams.

In a preferred embodiment, a single spreader calibration unit **335** controls each of the K pulse spreaders **330** in the i-th channel only. For this, the spreader calibrator **335** monitors each of the K imprinted code beams **332** and controls the K pulse spreaders **330** with a spreader control signal **336** to insure the accuracy and stability of each of the imprinted code beams **332**. In another embodiment, a spreader calibration unit **335** controls each of the K pulse spreaders **330** for all N channels.

Pulse Spreader

FIG. **4** is a block diagram of a preferred embodiment of the pulse spreader **330**. A portion of the pulsed light beam **318** is directed to the spreader calibration unit **335** while the code beam **322** is split by a 1:P splitter **410**, P representing the number of code bits (referred to a "chip") in each code word. In a preferred embodiment, the code beam is split into P=16 split beams, however, any number of split beams may be used and is within the scope of the invention. For purposes of clarity, FIG. **4** shows the modification of only one of the P split beams and it is understood that the remaining split beams are directed to structures identical to the chip modulators **450** of FIG. **4**.

Each of the P split beams is passed through a delay **420** that delays the split beam by a predetermined amount. In a preferred embodiment, the delay **420** is a multiple of TIP where T is the symbol period and P is the number of split beams or chips. In a preferred embodiment, the delay **420** may be a calibrated length of waveguide such as an optical fiber or a semiconductor waveguide. The delay increment, $C=TIP$, is referred to as a chip period and there are P chip periods per symbol period. In a preferred embodiment, a symbol period of T=400 ps is selected and P=16 is chosen, resulting in a chip period of C=25 ps.

The first split beam p=1 is not delayed, the second split beam p=2 is delayed by one chip period, the third split beam is delayed by two chip periods p=3, etc., and the pth split beam is delayed by p=(P-1) chip periods. The result of the family of delays **420** acting on the P split beams provides each split beam with a single pulse (preferably of length 10-20 ps), each pulse being positioned in a unique "time chip" within the symbol period T, the time chips being spaced apart in time by T/P. If the split beams are now combined, the repetition rate of the pulse train of the combined beam would be multiplied by a factor of P, or in the case of the instant example, would increase from 2.5 GHz to 40 GHz.

The split beams, however, are not combined immediately after the delays **420**. Instead, each delayed split beam is passed through a chip modulation circuit **430**. In a preferred embodiment, the chip modulation circuit **430** phase shifts each pulse by a predetermined amount, δ_{kp} , where δ_{kp} is the phase shift applied to the p-th chip of the k-th code. In a preferred embodiment, the chip modulation circuit **430** is an opto-electronic device such as a Pockels cell phase modulator. In another embodiment, the chip modulation circuit **430** may also apply an amplitude scaling, a_{kp} , to each split beam. Regardless of how the chip modulation circuit **430** is implemented, combiner **440** combines each of the delayed-and-now-chip-modulated split beams into a single code beam **332**. A portion of the code beam **332** exiting the combiner **440** is directed to the spreader calibration unit **335**.

The set of modulations provided by the chip modulator, $\{\delta_{k1}, \dots, \delta_{kP}; a_{k1}, a_{kP}\}$, uniquely identify the k-th code and are chosen to be orthogonal to each of the other (K-1) codes. The selection of the orthogonal code sets may be from any one of the orthogonal code sets known to one of skill in the signal processing arts. In a preferred embodiment, the modulation consists of phase shifts given by the following equation:

$$\delta_{kp} = \frac{2\pi(k-1)(p-1)}{P} \quad (1)$$

where p is the chip index varying from 1 to P where P is the number of chips per symbol period and k is the code index varying from 1 to K where K is the number of codes per channel. In the preferred embodiment, $K \leq P$.

Each chip modulation circuit **430** receives input from the spreader calibration unit **335** via a driver **435** belonging to the chip modulator **450**. The spreader calibration unit **335** determines the amount of phase shift and/or amplitude scaling each chip modulation circuit **430** applies to its respective split beam. The spreader calibration unit **335** adjusts each shift/scaling by a calibration offset that it determines. The spreader calibration unit **335** may be implemented in a digital signal processor (DSP) of the sort known to those skilled in the digital processing art. In a preferred embodiment, a single spreader calibration unit **335** controls the P chip modulating circuits **430** for all K codes. As will be clear to one of skill in the art, one may use multiple spreader calibration units, such as one for each of the K codes.

The chip modulation circuit **430** is essentially a static modulator because the modulation applied to each chip does not vary except for long term (with respect to the symbol period) drifts or slowly varying conditions such as temperature that are compensated by the spreader calibrator **335**. By splitting the code beam **322** into P chips and independently modulating each chip individually every symbol period, the k-th pulse spreader **330** creates an imprinted code beam that carries the code beam's identification at a modulation rate of P times the symbol rate using inexpensive (relative to dynamic modulators capable of modulating at P times the symbol rate) static modulators. However, an alternative to the pulse spreader **330** described above with respect to FIG. **4**, is to employ a pulse spreader having a dynamic code modulator capable of modulating the code beam **322** at P times the symbol rate, and this is also contemplated in the system of the present invention.

FIG. **5** is a block diagram of a preferred embodiment of the spreader calibration unit **335**. The spreader calibration

unit **335** adjusts the modulation applied by the chip modulation circuit **430** to ensure the K code beams remain orthogonal to each other. A portion of the imprinted code beam (ICB) **332** from each of the K pulse spreaders **330** is directed into an ICB switch **510**. In a preferred embodiment, a portion of the pulsed light beam **318** is directed into a CB switch **520**. A continuous-wave (CW) reference laser **530** generates a reference beam that is directed to both the ICB switch **510** and the CB switch **520** by splitter **532**. In an alternate embodiment, a portion of the K code beams (CB) **322** may be directed into the CB switch **520**.

At any instant, the ICB switch **510** selects one from among the K+1 inputs and directs the ICB-selected beam **512** to an optical phase detector **550**. In other words, the ICB switch **510** selects either one of the K beams **332** from pulse spreader **330** or the reference beam and sends the selected beam onwards.

At any instant, the CB selects either the reference laser beam, or the pulse light source beam. The CB switch **520** directs the selected beam to 1:P splitter **524** which splits the selected beam into P split beams. Each split beam is passed through a unique delay line **525**. Each delay line **525** adds a known delay to the split beam that corresponds to the delay of one of the P chips. For example, the p-th delay line will correspond to the p-th chip in each symbol period. The P split beams are directed into a calibrated chip switch **540**. The calibrated chip switch **540** selects one of the P delayed split beams and directs the selected delayed split beam **522** into the optical phase detector **550**. The optical phase detector **550** calculates the (complex) product of the ICB-selected beam **512** and the complex conjugate of the selected split beam **522**, giving the product of their amplitude and the phase difference between the two beams.

When the imprinted code beam **332** for code k is selected by ICB switch **510**, the p-th chip of the ICB-selected beam **512** will be proportional to $a_{kp} \cdot e^{j2\pi f(t-\tau_{kp})} \cdot e^{j\delta_{kp}}$, where f is the known beam frequency and δ_{kp} , a_{kp} and τ_{kp} are the preset phase shift, amplitude scaling and delay applied for the p-th chip by the k-th pulse spreader **330**. When the pulsed light beam **318** is selected by CB switch **520**, the selected split beam **522** will have a zero signal for all chips except for the chip corresponding to the selected delay line **525**. For example, if the split beam switch **540** selects the second delay line corresponding to the second chip of the symbol period, the selected split beam will have a zero signal for the first chip period, a non-zero waveform in the second chip period, and zero signals for the third through P-th chip periods. Selected split beam **522** will be proportional to $e^{j2\pi f(t-\tau_p)}$ where τ_p is the known p-th delay selected by switch **540**.

Since the selected split beam **522** has a non-zero signal only for the p-th delay line (selected by the split beam switch **540**), the product determined by the optical phase detector **550** is equal to $a_{kp} \cdot e^{j2\pi f(\tau_p-\tau_{kp})} \cdot e^{j\delta_{kp}}$. Processor **560** measures the amplitude a_{kp} and the phase $\delta_{kp}-2\pi f(\tau_{kp}-\tau_p)$ and commands the spreader calibration unit **335**, for the k-th pulse spreader, to maintain a_{kp} and $\delta_{kp}-2\pi f\tau_{kp}$ at the required value given, for example, by equation 1.

Each of the P delay lines **525** (τ_p) are calibrated using the reference CW laser **530** (which may be tapped from CW laser **311**) as will now be described. The ICB switch **510** selects the reference laser beam and directs the beam to the optical phase detector **550**. CB switch **520** selects the reference laser beam and directs the reference beam to the 1:P splitter **524** where the reference beam is split into P split beams. Each split beam is directed to a delay line **525**. A calibrated chip switch **540** selects one of the delayed split

beams and directs the selected delayed split beam **522** to the optical phase detector **550**. The optical phase detector **550** determines the phase difference between the reference beam selected by the ICB switch **510** and the delayed reference beam selected by the split beam switch **540**. The reference beam is proportional to $e^{j2\pi f_0 t}$ where f_0 is the reference laser's known frequency and the delayed reference beam is proportional to $e^{j2\pi f_0(t-\tau_p)}$. The phase difference between the two reference beams, $2\pi f_0 \tau_p$, gives the delay of the selected delay line **525**. Processor **560** stores the phase differences for each of the delay lines **525**. Processor **560** also controls the switching of the ICB switch **510**, the CB switch **520**, and the split beam switch **540**.

It is understood in the above description of the spreader calibration circuit **335** of FIG. 5 that the various switches **510**, **520** and **540** are controlled by circuitry that has been omitted in the figure. In general, either processor **560**, or another controller, or the like, will govern the timing and selection of these switches.

FIG. 6 is a block diagram of another embodiment of a spreader calibration unit. In spreader calibration unit **335a**, an imprinted code beam (ICB) switch **610** selects one of the K imprinted code beams from the pulse spreader **330** and directs the selected imprinted code beam **612** into an optical phase detector **650**. A continuous-wave (CW) reference laser **620** generates a reference light beam **622** that is directed into the phase detector **650** after gate **630**. The gate may be implemented by a Mach-Zehnder intensity modulator or the like. The gate **630** allows the reference light beam **622** to pass through the gate **630** to the phase detector **650** only during a selected chip period. The selected chip period is determined by variable electronic delay **635**, which is controlled by processor **660**. The phase detector **650** determines the amplitude product of, and the phase difference between, the selected imprinted code beam **612** and the gated reference beam **632**. The amplitude product and phase difference are passed to a processor **660** that determines the offset that should be applied by the (kp)-th chip modulation circuit.

FIG. 7 presents a block diagram of the optical phase detector **550**, **650**, seen in FIGS. 5 and 6. The optical phase detector receives two optical beams **705**, **701** and generates two electrical signals **795**, **791** corresponding to the in-phase and quadrature components of the multiplication of **705** by the complex conjugate of **701**. One of the two beams, designated as A in FIG. 7, is referred to as a signal beam. The second optical beam **701**, designated as B in FIG. 7, is referred to for convenience as a reference beam in this description of the optical phase detector. It should be kept in mind, however, that the 'reference beam' **701** may be something other than an unmodulated train of pulses having no information.

The signal beam **705** is split into four beams identified by **715** in FIG. 7. In a referred embodiment, the signal beam **705** is split into four beams by a cascade of 1:2 splitters **710**. In another embodiment, the signal beam **705** may be directly split into four beams by a single 1:4 splitter. Regardless of how they are formed, the four signal beams **715** are directed into four 2:1 combiners **730a**, **730b**, **730c**, and **730d**.

The reference beam **701** is first subjected to a 1:2 splitter **720a** to form identical beams R1 and R2. Beam R1 is then subjected to a second 1:2 splitter **720b** to form identical beams R3 and R4. Meanwhile, Beam R2 is first subjected to a 180° phase shifter **724** before being split by 1:2 splitter **720c** to thereby form identical beams R5 and R6. Beam R3 is input as signal **721** to combiner **730a** while beam R4 is first subjected to a first 90° phase shifter **722a** before being input to combiner **730b** as signal **723**. Beam R5 is input as

13

signal **725** to combiner **730c** while beam **R4** is first subjected to a second 90° phase shifter **722b** before being input to combiner **730d** as signal **727**.

The resulting beams **R3**, **R4**, **R5** and **R6**, represented as signals **721**, **723**, **725**, and **727** are phase-shifted by 90° increments. Beam **R3/721** has zero phase shift and is combined with one of the four signal beams **715** in 2:1 combiner **730a** to produce first combined beam **731** that is the sum of the signal and reference beam, designated as $A+B$. Beam **R4/723** has a 90° phase shift and is combined with one of the four signal beams **715** in second 2:1 combiner **730b** to produce second combined beam **733** that is designated as $A+jB$. Beam **R5/725** has a 180° phase shift and is combined with one of the four signal beams **715** in third 2:1 combiner **730c** to produce third combined beam **735** that is the difference between the signal beam and reference beam and is designated as $A-B$. Finally, beam **R6/727** has a 270° phase shift and is combined with one of the four signal beams **715** in fourth combiner **730d** to produce fourth combined beam **737** that is designated as $A-jB$.

The first and third combined beams **731**, **735** are input to a first matched detector **740a**. The first matched detector **740a** includes light sensors **745a**, to thereby generate electrical signals **798a** that are proportional to the intensity difference between the first and third combined beams **731**, **735**. The light sensors **745a** are preferably photoelectric detectors such as p-n, p-i-n, or Schottky-barrier photodiodes, and are selected to generate substantially identical electrical signals for the same incident light beam. The electrical signals **798a** generated by the first matched detector **740a** are input to a first amplifier **750a**. The output signal **752** of the first amplifier **750a** is proportional to the in-phase difference between the signal beam **705** and the reference beam **170** ($\text{real}\{AB^*\}$).

The second and fourth combined beams **733**, **737** are directed to a second matched detector **740b** comprising matched light sensors **745b**, to thereby generate electrical signals that are proportional to the intensity difference between the second and fourth beams **733**, **737**. The electrical signals **798b** generated by the second matched detector **740b** are input into a second amplifier **750b**. The output signal **754** of the second amplifier **750** is proportional to the quadrature phase difference between the signal beam **705** and the reference beam **701** ($\text{imag}\{AB^*\}$). The splitters, phase shifters, combiners and detectors together comprise an optical 90° hybrid detector **799** that outputs the signals **798a**, **798b**.

The analog output from the amplifiers **750a**, **750b** are input to low pass filters **760a**, **760b**, respectively. The output of the lowpass filters is then subject to dc bias adjustment **770a**, **770b** based on bias signals **772**, **773**, respectively, provided by a controller (not shown) which estimates signal energy. The filtered and bias-adjusted analog signals **I'** and **Q'** on lines **775**, **777**, respectively, are converted to digital form by sample and hold ("S&H") units **780a**, **780b**, respectively, which are timed by synchronization input **781**. The output of the sample and hold units is sent on to analog-to-digital converters **790a**, **790b**, to form the in-phase **I 795** and quadrature **Q 791** signals which are subject to further processing, as is known to those skilled in the art.

Data Modulator

FIG. **8** is a block diagram of a preferred embodiment of a data modulator **340** in accordance with the present invention. The imprinted code beam **332** from pulse spreader **330** enters the data modulator **340** through a power splitter **810**. The power splitter **810** splits the imprinted code beam **332** into two beams, designated as **H** and **V**. The **H** and **V** beams

14

are each directed into separate 1:2 splitters **820a**, **820b**, although a 1:4 splitter may be used instead. The splitter **820a** splits the **H** beam into **H1** and **H2** components and directs one of these (**H2** in FIG. **8**), into a 90° phase shifter **825a**. Similarly, the splitter **820b** splits the **V** beam into **V1** and **V2** components and directs one (**V2** in FIG. **8**) into a 90° phase shifter **825b**.

Each of the four component beams are directed into a separate modulator **830a**, **830b**, **830c**, **830d** where the data stream **370** is modulated on the four component beams. As discussed above, the data stream DATA_{ijk} includes data to be encoded on the **H** and **V** polarizations of a single code word, depending on the index '**j**'. Thus, the data input to modulators **830a**, **830b** is the data corresponding to $j='H'$ and the data input to modulators **830c**, **830d** is the data corresponding to $j='V'$.

Control signals from a power balancer **345** ensure that the intensity of each data-modulated component beam is comparable to that of the others and ensures the orthogonality of the in-phase and quadrature components of the constellation. Thus, the power balancer may have inputs into one or both of the phase shifters **825a**, **825b** and the data modulators **830a**, **830b**, **830c**, **830d**.

In a preferred embodiment, each of the four component beams is modulated with one bit. The modulators **830a**, **830b**, **830c**, **830d** are each implemented as a Mach-Zehnder Interferometer (MZI), each applying an amplitude of 1 or -1 (00 or 180° phase shift) to the component beam depending on whether the bit state is a 0 or 1. In a preferred embodiment, the data is encoded in the changes of phase between one bit to the other, referred to as differential quadrature phase shift keying (DQPSK). As will be clear to one of skill in the art, the 90° shift may be applied after the bit modulator **830**. As will also be clear to one of skill in the signal processing arts, the modulator **830** may also be a phase modulator or a multilevel amplitude modulator thereby allowing any amplitude/phase modulation and encoding of a higher number of bits per symbol.

The modulated **H1** and **H2** component beams are combined in a first combiner **840a** to form a data-modulated beam **H'**. Similarly, the modulated **V1** and **V2** component beams are combined in a second combiner **840b** to form a data-modulated beam **V'**. The data-modulated beams **H'** and **V'** are then combined in a polarization beam combiner **850** that rotates the polarization plane of the **H'**-beam 90° to the polarization plane of the **V'**-beam and combines both beams into the data beam **342**. The combined **H'** and **V'** beams do not interfere because of their orthogonal polarization planes.

As will be clear to one of skill in the optical arts, the polarization state of **H'** and **V'** beams may also be converted to any two orthogonal polarizations (such as right circularly polarized beam and a left circularly polarized beam) before combining into the data beam and still maintain the orthogonality condition that prevents interference between the two beams.

Receiver

FIG. **9a** is a block diagram of one embodiment of channel receiver **260** in accordance with the present invention. After demultiplexing by the DWDM demultiplexer **230**, each channel beam, indicated by λ_i in FIG. **9a**, is directed into its own channel receiver **260** where the **K** data streams are recovered and converted into electrical signals for downstream processing. The channel beam first is directed into an Rx PMD compensator **910**. The Rx PMD compensator **910** adjusts the polarization state of the channel beam to compensate for PMD distortions to the channel beam during transmission of the channel signal through the optical fiber.

15

In a preferred embodiment, the Rx PMD compensator **910** is the Acrobat™ Polarization Control Module (PCM) from Corning Incorporated of Corning, N.Y. The PolarRITE™ Polarization Controller from General Photonics Corporation of Chino, Calif. may also be used as the Rx PMD compensator **910**. As seen in FIG. **9a**, the Rx PMD compensator **910** receives controls signals **1055** from the receiver unit circuitry **930** which performs the functions of data extraction and PMD control, as discussed further below.

The compensated channel beam is directed into a 1:K splitter **920**. The splitter **920** splits the compensated channel beam into K split beams **925**. Each of the K split beams **925** are directed into a code receiver **960**. Each code receiver **960** is configured to recover one of the K data-modulated codes from the split beam **925** and convert the data-modulated code into an electrical signal corresponding to the data stream **932**. For purposes of clarity, only one code receiver is shown in FIG. **9a** and it should be understood that the channel receiver **260** has a separate code receiver **960** for each of the K data streams in the channel signal.

Pulsed light source **940** is substantially similar to pulsed light source **310** at the transmitter, and can actually be tapped from source **310** in the “duplex” node arrangement of FIG. **2b**. Pulse light source **940** generates a reference optical signal, characterized by λ_r . The reference optical signal is directed into the receiver pulse spreader **950** of each of the code receivers **960**.

The structure and operation of the receiver pulse spreader **950** is substantially the same as the pulse spreader **330** described with respect to FIG. **4** with the amplitude scaling $1/a_{kp}$ instead of a_{kp} . Thus, the receiver pulse spreader **950** has an associated calibration unit (not shown) which operates in a manner similar to that described with respect to spreader calibration units **335** or **335a**. The receiver pulse spreader **950** modulates the reference optical signal to produce a reference imprinted code beam **955** corresponding to one of the K imprinted code beams used to carry the K data streams in the channel signal. The reference imprinted code beam **955** is directed into the receiver unit **930**, and the optical detection circuitry **1090** and the demodulation circuitry **1060** within the receiver unit **930** recovers the data stream **932** from the channel signal **925** corresponding to the reference imprinted code beam **955**.

The PMD controller portion **1050**, **1050b** within receiver unit **930**, has an associated DSP which outputs a PMD compensator signal **1055** which is fed back to the Rx PMD compensator **910** (depicted in FIGS. **2a** & **2b** as ‘**280**’), and a SOP compensator signal **1056** which is sent to the transmitter over auxiliary channel **290**.

Receiver Unit

FIG. **10** is a block diagram of one embodiment of the receiver unit **930** seen in FIG. **9a**. This unit **930** employs homodyne detection. A split beam signal **925** is directed into a polarizing beam splitter **1010** of the optical detection circuitry **1090**. The polarizing beam splitter **1010** splits the split beam **925** into its first and second orthogonal polarization components, designated as H and V in FIG. **10**.

The H-beam **1012** is directed to a variable delay **1015** controlled by a delay signal **1014** from a symbol synchronizer **1040**. The variable delay **1015** delays the H-beam to synchronize the H-beam to the V-beam **1011** so that the H-beam and V-beam comprising the same symbol appear at the demodulator at the same time (alternatively, the inverse delay can be applied to the V-beam). The delayed H-beam is directed into a first optical phase detector **1030a**. The V-beam **1011** is directed into a second optical phase detector **1030b**. Reference imprinted code beam **955** corresponding

16

to one of the K codes entering the receiver unit **930** is split by a 1:2 power splitter **1020**. The split reference code beams **1022a**, **1022b** are directed into optical phase detectors **1030a**, **1030b**, respectively.

Optical phase detector **1030a** generates a pair of digital signals H_i , H_Q , which represent the in-phase and quadrature components of the H beam. Optical phase detector **1030a** also generates a pair of analog signals H'_i , H'_Q , which represent the analog versions of H_i , H_Q from which the digital signals were formed. Similarly, optical phase detector **1030b** generates a corresponding pair of digital signals V_i , V_Q , which represent the in-phase and quadrature components of the V beam, and the associated analog signals V'_i , V'_Q . The timing of the phase detectors **1030a**, **1030b** are controlled by a timing signal **1242** from the symbol synchronizer **1040**.

The four analog signals H'_i , H'_Q , V'_i , V'_Q are input into the symbol synchronizer **1040** and the digital signals H_i , H_Q , V_i , V_Q are input into the PMD controller/digital data demodulator circuit **1045**. The data and the PMD control signals are ultimately extracted from the digital signals, while symbol synchronization is performed using the analog signals.

The PMD controller **1050** receives the digitized I and Q components of the H and V polarizations and output the polarization control signals in response thereto. The PMD controller **1050** (see FIG. **10a**) determines the amount of PMD the optical signal has experienced and provides a compensation signal **1055** to the PMD compensator **910**. The four signals are further digitally processed in the digital data demodulator **1060** to recover the data stream **932**. As will be clear to one of skill in the signal processing art, the digital data demodulator **1060** may include components such as an equalizer, differential demodulation, frequency compensation and symbol timing recovery. In a preferred embodiment, the components are implemented as algorithms/computer programs executing on a DSP, FPGA, ASIC or other processor known, to one of skill in the signal processing art.

FIG. **10a** shows a conceptual configuration of data flow in a PMD controller/digital data demodulator circuit **1045** used in conjunction with a receiver having a receive signal PMD compensator **910** at the receiver front end, such as seen in the receiver **260** of FIG. **9a**. As discussed above, the optical detection circuitry **1090** outputs the I and Q components of the H and V polarizations of the incoming signal **925**. In FIG. **10a**, the output S of the optical detection circuitry **1090** represents the digital signals H_i , H_Q , V_i , V_Q , which have already been PMD compensated. These four signals are input into both the digital data demodulator **1060** and also to the digital PMD controller **1050**. The PMD controller, in turn, outputs a PMD controller signal **1055** which is fed to the receiver's PMD compensator **910**, and also outputs a SOP controller signal **1056** which is fed back to the transmitter's SOP compensator. Thus, the shown digital polarization compensator system provides feedback to both the receiver input and the transmitter output. And, as stated above, the digital PMD controller **1050** and the digital data demodulator **1060** are preferably implemented as algorithms in computer software.

FIG. **10b** shows a conceptual configuration of data flow in a PMD controller/digital data demodulator circuit **1045** of the sort used with a receiver having back-end digital PMD compensation **1050c**, instead of an input PMD compensator **910**, as seen in FIG. **9a**. In this instance, the uncompensated digital output S' of the optical detection circuitry **1090** is first subject to digital PMD compensation to thereby produce a PMD compensated digital signal S. The signal S is then

17

input to a digital PMD compensation controller **1050b** which performs the necessary calculations and adjustments to provide the needed digital PMD compensation. It is understood that the configuration in FIG. **10b** is used with a receiver not having a front-end PMD compensator, and so no signal **1055** is provided to a compensator device such as the aforementioned Acrobat™ Polarization Control Module (PCM). However, in the configuration of FIG. **10b**, one may optionally still have a signal **1056b** that is sent back to the transmitter **250** for transmitter-end SOP compensation.

FIG. **9b** is a block diagram of another embodiment of a channel receiver suitable for use with the present invention. Channel receiver **260a** employs self-homodyne detection, thereby obviating a need for a pulsed light source **940** of the sort used in channel receiver **206**.

The incoming channel beam **925** is first input to a receiver-end PMD compensator **1105** and resulting compensated signal is input to a 1:K splitter **1107** to create K identical compensated signals, one for each code word. Each of these is then split by a polarizing beam splitter **1110** into two beams having orthogonal polarization states designated by H and V in FIG. **9b**. It should be kept in mind that since the 1:K splitter **1107** is a linear device, it may instead be positioned either before the PMD compensator **1105** or the polarization beam splitter **1110**.

The H-beam **1112** is directed to a variable delay **1115** controlled by a signal **1114** from the symbol synchronizer **1150**. The variable delay **1115** delays the H-beam so as to synchronize the H-beam to the V-beam **1111** so that the H-beam and V-beam comprising the same symbol appear at the demodulator at the same time. It should be understood that one may instead delay the V beam instead of the H beam.

The polarized H and V beams **1112**, **1111** are first directed into despreaders **1120a**, **1120b**, respectively, which leave the H and V beams only with phase information of the data used to modulate the code word for which the despreaders **1120a**, **1120b** are attuned. After despreading, the H beam is subjected to a first 1:2 splitter **1130a**, to form identical beams H1 and H2, represented as signals **1131a**, **1132a**, respectively. After despreading, the V beam is subjected to a second 1:2 splitter **1130b** to form identical beams V1 and V2, represented as signals **1131b**, **1132b**, respectively. Beams H2 and V2 are directed into symbol period delay circuits **1135a**, **1135b**, respectively, to thereby delay H2 and V2 by one symbol period. Beam H1 and one-symbol-period-delayed beam H2 are then input to a first optical phase detector **1140a**, while beam V1 and one-symbol-period-delayed beam V2 are input to a second optical phase detector **1140b**. Thus, the optical phase detectors **1140a** and **1140b** will output information about the symbol-to-symbol phase difference, which is useful in differential phase shift keying (DPSK).

The two optical phase detectors **1140a**, **1140b** output four digital signals designated as H_i , H_Q , V_i , and V_Q that represent the in-phase and quadrature information of the H and V-beams. They also generate the four analog signals H'_i , H'_Q , V'_i , and V'_Q , that correspond to the digital signals. The timing of the phase detectors **1140a**, **1140b** is controlled by a timing signal **1242** from the symbol synchronizer **1150**. The four digital signals are input to the PMD controller/digital data modulator **1145**, much as discussed above with respect to the device **1045** of FIG. **10**.

The structure of the Rx code despreaders **1120a**, **1120b**, is substantially the same as the pulse spreader **330** shown in FIG. **4**. The principle difference between an Rx code

18

despreader **1120a**, **1120b** and the pulse spreader **330** is in the amplitude scaling and modulation applied to the pulse beam. For the k-th code despreader, the delay for the p-th chip, τ_p^* , is the complement of the delay for the p-th chip in the k-th pulse spreader, τ_p . Similarly, the Rx despreader phase shift, δ_{kp}^* , is the conjugate phase shift applied by the pulse spreader **330** and the despreader amplitude, a_{kp}^* , is inverse of the amplitude scaling applied by the pulse spreader **330**. The despreader delays and modulations are given by the equations:

$$\tau_p^* = T - \tau_p \quad (2)$$

$$\delta_{kp}^* = -\delta_{kp} \quad (3)$$

$$a_{kp}^* = 1/a_{kp} \quad (4)$$

Thus, within the K pairs of despreaders, each despreader **1120a**, **1120b** belonging to k-th pair is attuned to the k-th code word. As discussed above, the polarized H and V beams **1112**, **1111** contain the entire code division multiplexed optical signal comprising all K orthogonal code words modulated with data. When the H and V beams **1112**, **1111** enter the k-th pair of despreaders, the output of that pair of despreaders is only the phase of the data modulated on the k-th code word, present at a known location within the symbol. This is because the k-th pair of despreaders counters the code modulation of the k-th code word, leaving only the phase of the data modulation in a known position (due to the time-shifting of the time chips brought about by delay for the p-th chip, τ_p^*), while the remaining K-1 code words, being orthogonal to the k-th code word, more or less cancel out.

The despreaders **1120a**, **1120b** are calibrated by calibration unit **1125** which operates in a manner similar to that described with respect to spreader calibration units **335** or **335a**.

In the preferred embodiment using the coding scheme described by equation (1), the despreader delay and modulation for code k is identical to the pulse spreader delay and modulation for code k. In a preferred embodiment, the upstream channel transmitter may be integrated with the downstream channel receiver and vice versa. In such a situation, the imprinted code beams **322** generated by the pulse spreader **330** for the upstream transmitter may be used as the K reference code beams. For a generalized coding scheme encompassed by the present invention allowing both phase and amplitude modulation, however, the despreader may not be identical to the pulse spreader.

FIG. **11** is a block diagram of the optical phase detectors **1030a**, **1030b** seen in the optical detection circuitry **1090** of FIG. **10** and the optical phase detectors **1140a**, **1140b** seen in the channel receiver **260a** of FIG. **9b**. The phase detector receives two optical beams **1705**, **1701** and outputs generates two electrical signals **1795**, **1791** corresponding to the in-phase and quadrature components of the signal beam. One of the two beams, designated as A in FIG. **7**, is a signal beam. The second optical beam **1701**, designated as B in FIG. **11**, is a reference beam.

The signal beam **1705** is split into four beams identified by **1715** in FIG. **11**. In a preferred embodiment, the signal beam **1705** is split into four beams by a cascade of 1:2 splitters **1710**. In another embodiment, the signal beam **1705** may be directly split into four beams by a single 1:4 splitter. Regardless of how they are formed, the four signal beams **1715** are directed into four 2:1 combiners **1730a**, **1730b**, **1730c**, and **1730d**.

The reference beam **1701** is first subjected to a 1:2 splitter **1720a** to form identical beams R1 and R2. Beam R1 is then

subjected to a second 1:2 splitter **1720b** to form identical beams **R3** and **R4**. Meanwhile, Beam **R2** is first subjected to a 180° phase shifter **1724** before being split by 1:2 splitter **1720c** to thereby form identical beams **R5** and **R6**. Beam **R3** is input as signal **1721** to combiner **1730a** while beam **R4** is first subjected to a first 90° phase shifter **1722a** before being input to combiner **1730b** as signal **1723**. Beam **R5** is input as signal **1725** to combiner **1730c** while beam **R6** is first subjected to a second 90° phase shifter **1722b** before being input to combiner **1730d** as signal **1727**.

The resulting beams **R3**, **R4**, **R5** and **R6**, represented as signals **1721**, **1723**, **1725**, and **1727** are phase-shifted by 90° increments. Beam **R3/1721** has zero phase shift and is combined with one of the four signal beams **1715** in 2:1 combiner **1730a** to produce first combined beam **1731** that is the sum of the signal and reference beam, designated as **A+B**. Beam **R4/1723** has a 90° phase shift and is combined with one of the four signal beams **1715** in second 2:1 combiner **1730b** to produce second combined beam **1733** that is designated as **A+jB**. Beam **R5/1725** has a 180° phase shift and is combined with one of the four signal beams **1715** in third 2:1 combiner **1730c** to produce third combined beam **1735** that is the difference between the signal beam and reference beam and is designated as **A-B**. Finally, beam **R6/1727** has a 270° phase shift and is combined with one of the four signal beams **1715** in fourth combiner **1730d** to produce fourth combined beam **1737** that is designated as **A-jB**. Thus combiners **1730a**, **1730b**, **1730c** and **1730d** are configured to combine a copy of signal **A** with a copy of signal **B** shifted by 0°, 90°, 180° and 270°, respectively, to output first **1731**, second **1733**, third **1735** and fourth **1737** combined beams, respectively.

The first and third combined beams **1731**, **1735** are input to a first matched detector **1740a**. The first matched detector **1740a** include light sensors **1745a**, to thereby generate electrical signals that are proportional to the intensities of the first and third combined beams **1731**, **1735**. The light sensors **1745a** are preferably photoelectric detectors such as p-n, p-i-n, or Schottky-barrier photodiodes, and are selected to generate substantially identical electrical signals for the same incident light beam. The electrical signals **1798a** generated by the first matched detector **1740a** are input to a first amplifier **1750a**. The output signal **1752** of the first amplifier **1750a** is proportional to the in-phase difference between the signal beam **1705** and the reference beam **1701**.

The second and fourth combined beams **1733**, **1737** are directed to a second matched detector **1740b** comprising matched light sensors **1745b**, to thereby generate electrical signals that are proportional to the intensities of the second and fourth beams **1733**, **1737**. The electrical signals **1798b** generated by the second matched detector **1740b** are input into a second amplifier **1750b**. The output signal **1754** of the second amplifier **1750** is proportional to the quadrature phase difference between the signal beam **1705** and the reference beam **1701**. The splitters, phase shifters, combiners and detectors together comprise an optical **900** hybrid detector **1799** that outputs the signals **1798a**, **1798b**.

The electrical signals **1798a**, **1798b** from the optical **900** hybrid detector **1799** are next input to a signal conditioning cascade circuit for comprising an amplifier, a low pass filter, DC bias removal, sample and hold circuitry and analog-to-digital converter. Signals **1798a**, **1798b** are first amplified by amplifiers **1750a**, **1750b**, respectively. The analog output from the amplifiers **1750a**, **1750b** are input to low pass filters **1760a**, **1760b**, respectively. The low pass filters preferably operate at 40 GHz. The output of the lowpass filters is then subject to dc bias adjustment **1770a**, **1770b** based on bias

signals **1772**, **1773**, respectively, provided by a controller (not shown) which estimates signal energy. The filtered and bias-adjusted analog signals **I'** and **Q'** on lines **1775**, **1777**, respectively, are converted to digital form by sample and hold ("S&H") units **1780a**, **1780b**, respectively, which are timed by synchronization input **1781**. The output of the sample and hold units is sent on to analog-to-digital converters **1790a**, **1790b** to form the in-phase **I** **1795** and quadrature **Q** **1791** signal which are subject to further processing, as is known to those skilled in the art.

The filtered and bias-adjusted analog signals **I'** and **Q'** on lines **1775**, **1777**, respectively, are also sent on to the symbol synchronization units **1040**, **1150**. Thus, the optical phase detector of FIG. **11** used in conjunction with the receiver is substantially similar to that shown in FIG. **7** for use on the transmitter side, with the exception of the analog taps for the symbol synchronization units.

Symbol Synchronization

FIG. **12** is a block diagram of a preferred embodiment of the symbol synchronization unit **1040/1150**. Analog **I'** and **Q'** signals on lines **1775**, **1777** from both the **H** and **V** optical phase detectors, representing both the in-phase and quadrature-phase components of the selected code beam, are each input into an early gate **1210** and a late gate **1215**.

The early gate **1210** samples the signal a fraction of a symbol time before the S&H units **1780a**, **1780b** in the optical phase detector **1030a**, **1030b/1140a**, **1140b** perform their sampling. Conversely, the late gate **1215** samples the signal a fraction of a symbol time after the S&H units in the optical phase detector perform their sampling. In a preferred embodiment, the magnitude of the time offsets for the early and late gates are identical and equal to $T/5$ where T is the symbol period.

Each gate **1210**, **1215** comprises a sample & hold unit followed by an analog-to-digital converter, and is controlled by a clock signal from the clock distribution unit **1295**. The signal from the clock distribution unit **1295** controls the sample & hold unit in each gate **1210**, **1215** and determines the sampling instance of the input analog signals **1775**, **1777** by each gate **1210**, **1215**. The analog-to-digital converter converts the analog sampled signal to digital format.

The in-phase and quadrature components from each of the gates **1210**, **1215** are squared **1220** and summed **1225** to determine the symbol energy for each gate. The symbol energies are indicated in FIG. **12** as **HE**, **HL**, **VE** and **VL** where **H** and **V** designate the polarization states and **E** and **L** represent the early or late gate averages. The four symbol energies are input into separate delays **1230** and subtractors **1235**. The delay **1230** delays the signal representing the symbol energy by one symbol period before sending the signal to the subtractor **1235**. The subtractors **1235** determine the differences between the preceding symbol energies and the current symbol energies. The absolute value of the symbol-to-symbol energy difference is taken in **1240**. The difference between the early gate and late gate energy difference is determined by subtractor **1245**.

Averager **1250** averages the early/late gate symbol-to-symbol energy difference and inputs the output of the averager **1250** to a synchronizer loop filter **1270**. The synchronizer loop filter **1270** controls a voltage controlled oscillator (VCO) **1280** that generates a timing signal **1242** that is distributed by a clock distribution unit **1295** to the early and late gates of the synchronizer and to the optical phase detectors.

Thus, with reference to FIG. **10**, the symbol synchronizer **1040** receives the in-phase and quadrature components of the first and second orthogonal polarization components of

split beam signal **925**, and outputs a timing signal **1242** to help synchronize the symbol boundaries of the data-modulated codewords in the optical phase detectors **1030a**, **1030b**.

In the preferred implementation, the signal from the H and V channels are averaged to control a single VCO. In another implementation, only one channel is used to control the VCO. In yet another implementation, each of the channels may control a different VCO.

Subtractor **1255** determines the difference between the symbol-to-symbol energy differences from the H and V optical phase detectors. The difference between the H and V optical phase detectors is input into the delay loop filter **1260**. The delay loop filter **1260** generates a control signal **1014/1114** to the H-beam variable delay **1015/1115** based on the symbol-to-symbol energy difference between the H and V optical phase detectors.

In the above implementation of the symbol synchronizer **1040**, **1150**, it is noted that the various computations are preferably performed in software by a DSP, ASIC or another, preferably programmable, processor.

FIGS. **13a** and **13b** illustrate the advantage of using the symbol-to-symbol energy difference, instead of using just the symbol energy. FIG. **13(a)** is a graph of the average symbol energy **1310** as a function of the normalized symbol time. A symbol time of zero corresponds to the beginning of a symbol. An energy envelope **1315** approximately indicates the variation that can be expected in the symbol energy measurement as a function of symbol time. The energy envelope exists because the signal still contains the signals from the other combined codes of the channel. The average symbol energy **1310** exhibits a slight maximum **1320** when the symbol time is synchronized to the symbol. The slight maximum makes it very difficult to locate the maximum in the symbol energy curve.

FIG. **13(b)** is a plot of the average symbol-to-symbol energy difference **1350** as a function of the symbol time. An energy envelope **1360** approximately indicates the variation that can be expected in the symbol-to-symbol energy difference measurement as a function of symbol time. The average symbol-to-symbol energy difference **1350** exhibits a relatively deep minimum **1370** when the symbol time is synchronized to the symbol. The relatively deep minimum allows the loop filter to locate and keep the symbol time at the minimum **1370**.

Polarization Compensation

FIG. **14a** is a block diagram of a communication system **1400** that is able to adjust the SOP of the transmitted signal such that the transmitted signal is launched along the axes of the fiber **1474** associated with the minimum spreading of the received signal, while also compensating for the received PMD. In theory, the fiber exhibits two orthogonal eigenstates that are independent of frequency and fiber length. When the signal is launched along these eigenstates (fast and slow axes) of the fiber, PMD is limited to the differential group velocities of the two, and coupling of the signal's components traveling along each of the axes is zero. In practice, there are no such eigenstates for the long fiber, but for each optical frequency there exist two orthogonal input polarization states for which the output polarization states exhibit the least frequency dependence. Such states are called the principle state of polarization (PSP) of the fiber; the signal launched along the PSP exhibits the least coupling and therefore, the minimal temporal spreading. Due to environmental variations along the fiber with time, the PSP also varies with time and the variations should be tracked and compensated for.

The communication system **1400** includes a transmitter **1470** that directs the multiplexed and modulated optical signal to a transmitter polarization compensator **1472** that adjusts the transmitter SOP (Tx SOP) before launching the optical signal through the optical fiber **1474**. At the receiver, a receiver polarization compensator **1476** adjusts the receiver SOP (Rx SOP) to optimize the selected metric. The receiver **1478** includes a PMD controller control both the receiver polarization compensator **1476** via signal line **1477** and the transmitter polarization compensator **1472** via a supervisory channel **1473** (represented by line **295** in FIGS. **2a** and **2b** and lines **1056**, **1156** in FIGS. **9a**, and **9b**, respectively). The compensators **1472** and **1476** are discrete devices such as described above. The PMD controller may be implemented in hardware but in a preferred embodiment, the controller is implemented as a computer program executing on a processor such as a DSP.

FIG. **14b** presents a flow diagram **1405** describing the operation of the PMD controller Rx module for controlling the Rx SOP. The PMD controller dithers the receiver PMD compensator and executes a search to determine the compensation required to optimize some metric. In a preferred embodiment, the metric is the symbol signal-to-noise-ratio (SNR), and this is to be maximized. It should be noted, however, that one may instead use the error vector magnitude (EVM) as the metric, and minimize this. Other metrics may also be employed.

In step **1410**, the dither step parameters, which include dither size and dither direction are established. The size and direction are established with respect to movement on the surface of a Poincare' sphere representing the receiver's SOP. The step directions are with respect to rotations, $\Delta\theta$ and $\Delta\epsilon$, about the H-V and P-Q axes, respectively. Each dither step comprises a pair of rotations. Each rotation can take three possible values ($\pm\Delta\theta$ and 0 for the H-V rotation and $\pm\Delta\epsilon$ and 0 for the P-Q rotation) resulting in a total of nine dither steps. Thus, establishing the dither step parameters entails selecting one from among nine candidate steps.

In step **1420**, the receiver's PMD compensator is dithered by one of candidate steps by applying the proper set of rotations. In step **1430**, the metric to be optimized is estimated by the controller and stored along with the state of the receiver PMD compensator **1476**, the state being reflective of the candidate step that had just been tried. Techniques for estimating a metric such as the SNR are well-known and standard algorithms for this can be executed by the processor. The signals used for this preferably are known pilot signals sent by the transmitter, and the receiver knows what to expect.

In step **1440**, a check is made to determine whether all candidates have been tried. If not, control returns to step **1410** to try the next candidate step. If, on the other hand, all candidate steps have been tried, control flows to step **1450**. In step **1450**, the candidate step/PMD compensator state corresponding to the optimized metric (e.g., highest SNR) is determined and in step **1460**, the PMD compensator is adjusted to the optimized state/location on the Poincare' sphere. For this, the PMD controller commands the receiver PMD compensator **1476** through signal line **1477** to execute the optimal adjustment in **1460**. Preferably, the above process is repeated until some terminal condition is met. The terminal condition can be convergence, i.e., there are no more changes in state, or upon completion of a predetermined number of dithering loops. The desirable result from this process is to restore the signal polarization components by re-aligning the RX SOPs with the TX SOPs.

23

While the above description calls for an exhaustive search through all possible candidate steps, it should be kept in mind that fewer than all possible steps can be tried. In a preferred embodiment, the dither adjustment is determined by a steepest gradient method. This allows one to reduce processing time (such as by choosing larger step sizes) in exchange for a slightly elevated risk that one misses the global optimum on the Poincare' sphere, when searching for an optimum metric.

After determining the optimal adjustment, The PMD controller Rx module described above with respect to FIG. 14b can find the optimum state for the receiver PMD compensator 1476 to compensate for the SOP transformation taking place in the fiber at the receiver end of the system. This will not, however, compensate for spreading of the signal caused by the frequency dependence of the transmitted signal's SOP if it does not coincide with the PSP axes of the fiber. For this, one must also compensate the transmitted signal, before it is transmitted.

FIG. 14c presents a flow diagram 1480 describing the operation of the PMD controller Rx/Tx module to control both the receiver PMD compensator 1476 and the transmitter SOP compensator 1472, in a system such as that seen in FIG. 14a.

In step 1482, the PMD controller adjusts the Rx compensator to re-align the Rx and Tx SOPs by dithering only the receiver, as discussed above with respect to flow diagram 1405 in FIG. 14b. This means that the incoming signal is being properly compensated at the receiver.

Beginning with step 1484, the controller next searches for the PSP of the fiber by examining the ensemble of the candidate SOPs on the Poincare' sphere for the transmitter. In this regard, it is noted that the Tx SOP candidates are assumed to be uniformly distributed on the transmitter's Poincare' sphere with certain resolution—i.e., each candidate is “assigned” some portion of the sphere; the larger the number of candidates, the smaller the portion size.

Thus, in step 1484, a candidate Tx SOP is selected, and the Tx compensator is adjusted accordingly.

In step 1486, the receiver SOPs are adjusted to conform the new candidate Tx SOP so as to preserve the TX/RX SOP alignment. This is done by adjusting the receiver PMD compensator in a manner complementary to the adjustment made to the transmitter compensator. In effect then, a rotation of the Tx compensator 1472 to a new candidate SOP is followed by a “counter-rotation” of the Rx compensator 1476. To ensure synchrony between the transmitter and the receiver, the Tx SOPs preferably are adjusted on some predetermined basis that is known to the receiver so as to allow the Rx SOPs to be changed each time a new Tx candidate SOP is tried.

In step 1488, the relevant metric is calculated and stored, along with the states of the Tx SOPs and the Rx SOPs. The optimal TX SOP (i.e., the PSP) are chosen based on the same criteria as used by the RX compensator (e.g., maximum SNR).

In step 1490, a check is made to determine whether all the candidate Tx SOPs have been evaluated. If it is determined in step 1490 that additional candidate Tx SOPs remain, these are tried. If, on the other hand, it is determined in step 1490 that there are no further candidate Tx SOPs, controls flows to step 1492.

In step 1492, the transmitter and receiver compensators 1472, 1476, respectively, are adjusted based on the states corresponding to the optimum metric. Thus, the final TX/RX SOP adjustment takes place to align the TX SOP with the PSP axes.

24

The above-described procedure is repeated to track the polarization changes occurring in the fiber. Preferably, this is done on a continuous basis. The candidate PSP list can be limited to the subset of the original list situated around the current PSP axes during the tracking. This limitation is based on the assumption that the small variations in the fiber polarization transformation matrix will lead to small variations of the PSP orientation.

In the above-described operation of the PMD controller, the Receiver and Transmitter compensators are preferably implemented using the aforementioned Acrobat™ Polarization Control Module (PCM). It should be kept in mind, however, that other adjustable polarization control devices may be used, as well.

Transmitter Having Multiple Coding Stages

FIG. 15 is a block diagram 1500 of an alternative channel transmitter configured to create a code division multiplexed signal in accordance with the present invention. The channel transmitter 1500 creates the code words in two stages: a pre-coding stage 1502 and a final coding stage 1504. In the following description, K represents the total number of code words that are created, P represents the number of time chips in a code, and L represents the number of code words created from each pre-coding stage. In a preferred embodiment described below, K=16, P=16 and L=4, and the symbol period T=400 ps.

The channel transmitter 1500 includes a pulsed light source 1510 which generates an optical pulse stream 1515. The optical pulse stream 1515 preferably comprises pulses separated by $T \cdot UK = 100$ ps, given the preferred parameters. Thus, an optical pulse stream from source 1510 having a symbol length T=400 ps has a total of 4 pulses, each pulse being found in a single 100 ps window. This contrasts with the pulse spacing of 400 ps provided by the pulsed light source 310 in the embodiment of FIG. 3. Accordingly, the pulsed light source 1510 outputs pulse 4 times as fast as pulsed light source 310.

The optical pulse stream 1515 is directed into a 1:K/L splitter 1520 to produce K/L identical optical pulse streams 1525. Each identical optical pulse stream 1525 is then subject to a separate dynamic code modulator (DCM) 1530a, 1530b, 1530c, 1530d to create a corresponding sub-code beam 1535a, 1535b, 1535c, 1535d. Each DCM imparts a first phase shift to each of the pulses input thereto, based on pre-determined control signals from a DCM controller 1532. The resulting sub-code beams 1535a, 1535b, 1535c, 1535d preferably are orthogonal to one another. For clarity, further processing applied to only one sub-code beam 1535a is discussed, it being understood that the remaining sub-code beams 1535b, 1535c and 1535d undergo the same processing.

The sub-code beam 1535a is directed into a 1:L splitter to form four identical sub-code beams 1545a, 1545b, 1545c, 1545d having the same set of phase shifts. In general, L represents the number of code words created by a sub-code beam. Thus, each of the L=4 identical sub-code beams is then directed into a corresponding pulse spreader 1550a, 1550b, 1550c, 1550d. Pulse spreaders 1550a, 1550b, 1550c, 1550d are configured work substantially the same as pulse spreader 330 seen in FIG. 4, except that the spreader splitter performs a 1:PLK split (PL/K being an integer) and the spreader combiner forms a PUK:1 combination. Thus, for example, pulse spreader 1550a includes a 1:PL/K splitter, delay circuitry for PL/K delays, chip modulation circuitry, and a PL/K:1 combiner. A spreader calibration unit 1585 controls the spreaders, in a manner analogous to spreader

25

calibration units **335**, **335a**, described above. And for $P=16$, $K=16$, $L=4$; $PL/K=4$, as seen in FIG. **15**.

A sub-code beam **1545a** comprising a 400 ps-long symbol of four pulses spaced apart from one another by 100 ps enters the pulse spreader **1550a**. Within pulse spreader **1550a**, the first of the four pulses arrives in the first 100 ps window and is subject to a 1:4 split to create 4 identical copies. Delays of 0 ps, 25 ps, 50 ps and 75 ps are applied to each of the 4 split pulses, a chip modulation circuit then applies a second phase shift (or applies both a second amplitude and phase) to each of the four split pulses, and the code-modulated four split pulses are recombined in a 4:1 combiner. This results in four code-modulated pulses within the first 100 ps window, each pulse having been modulated twice: once by the dynamic code modulator **1530a** in the first stage **1502**, and a second time by a chip modulating circuit associated with the pulse spreader **1550a** in the second stage **1504**. The second, third and fourth pulses belonging to sub-code beam **1545a** arrive in the second, third and fourth 100 ps windows of the symbol, respectively. They are similarly split, delayed, subject to a second phase shift by the same pulse spreader **1550a**, and then recombined.

Thus, the output of the pulse spreader **1550a** is thus a single code word **1555a** having a total of $P=16$ pulses. Similarly, the output of the other pulse spreaders **1550b**, **1550c**, **1550d** are different code words **1555b**, **1555c**, **1555d**, respectively, each of the four code words originating from the sub-code word **1535a** being orthogonal to the other three, and also to the other 12 code words originating from the other three sub-code words **1535b**, **1535c**, **1535d**.

The ensemble of code words next enters a data modulation stage comprising data modulators **1560a**, **1560b**, **1560c**, **1560d**. Code word **1555a** enters the data modulator **1560a** where the data from a data stream **1570** under the control of a data controller (not shown) is imprinted thereon to thereby form a data-modulated code word **1565a**. This process is repeated for code words **1555b**, **1555c**, **1555d** with data modulators **1560b**, **1560c**, **1560d**, respectively, to form data-modulated code words **1565b**, **1565c**, **1565d**, respectively. These four data-modulated code words, along with the other 12 code words originating from the other three sub-code words **1535b**, **1535c**, **1535d** (for a total of $K=16$ code words), are then input to a 1:K combiner **1580** to create the data beam **1575** which is directed into a DWDM multiplexer (not shown). The data beam is thus a division multiplexed optical signal comprising orthogonal code words that have been data-modulated, the code words preferably having H and V polarizations due to a polarization beam combiner within the data modulators.

The transmitter **1500** is provided with one or more spreader calibration units **1585**, which behave in a manner similar to those discussed above. Thus, the spreader calibration units **1585** receive inputs from a reference light source **1518** and also from the outputs of the pulse spreaders **1555a**, **1555b**, **1555c**, **1555d** on lines **1556**. The spreader calibration units **1585** also output signals to these pulse spreaders, to ensure that each of the pulse spreaders has proper modulation.

The invention described and claimed herein is not to be limited in scope by the preferred embodiments herein disclosed, since these embodiments are intended as illustrations of several aspects of the invention. Any equivalent embodiments are intended to be within the scope of this invention. Indeed, various modifications of the invention in addition to those shown and described herein will become apparent to

26

those skilled in the art from the foregoing description. Such modifications are also intended to fall within the scope of the appended claims.

What is claimed is:

1. A code division multiplexed optical communication system comprising:

at least one transmitter configured to receive a first data stream and transmit a code division multiplexed optical signal comprising a number K code words modulated with first data from said first data stream (where K is an integer greater than 1);

wherein the transmitter comprises:

a pulsed light source;

a transmitter splitter having a splitter input and a plurality of splitter outputs, the transmitter splitter having the pulsed light source input thereto and outputting at least a number K identical code beams; K code modulators, each code modulator configured to receive one of the at least K identical code beams and output a corresponding data-modulated code word; wherein each of the code modulators comprises: a pulse spreader configured to receive one of the K identical code beams, said one of the K identical code beams comprising a single pulse within a predetermined time window, the pulse spreader being further configured to output an imprinted code beam having a number P modulated pulses within that time window; and a data modulator configured to receive said imprinted code beam from the pulse spreader and modulate said imprinted code beam with data from said first data stream to thereby form a data-modulated code word; wherein the pulse spreader comprises:

a 1:P splitter configured to split one of said K code beams input thereto into P identical code beams (where P is an integer greater than 1), each code beam having a single pulse; P chip modulators, each chip modulator configured to receive a single pulse and output a delayed modulated pulse, the p-th chip modulator comprising: a delay circuit configured to delay said single pulse by $(p-1)*C$, where $C=T/P$ is a chip period, T being a symbol period (T is an integer greater than 1) and p representing an index; and a chip modulation circuit configured to code-modulate the delayed single pulse by a p-th code value belonging to an orthogonal code of length P; and a P:1 combiner configured to combine code-modulated outputs from the P chip modulation circuits into the imprinted code beam which comprises P pulses within said symbol period T; and

a transmitter combiner configured to combine the K data-modulated code words into a code division multiplexed optical signal; wherein the K data-modulated code words are orthogonal to one another; and

at least one receiver optically connected to the first transmitter and configured to receive said code division multiplexed optical signal, detect and demodulate said K code words within the code division multiplexed optical signal, and output said first data, wherein the K code words are orthogonal to one another.

2. The optical communication system of claim 1, wherein the transmitter further comprises a spreader calibration unit which receives the imprinted code beam from the pulse spreader and a reference light source as inputs, and outputs a spreader control signal which is sent to the pulse spreader.

3. The optical communication system of claim 1 wherein the data modulator comprises: splitter circuitry configured to split the imprinted mode beam into identical first (H1), second (H2), third (V1) and fourth (V2) component beams; a first phase shifter configured to impart a 90.degree. phase shift the second component beam (H2); a second phase shifter configured to impart a 90.degree. phase shift to the fourth component beam (H4); a first modulator configured to modulate the first component beam (H1) with first data; a second modulator configured to modulate the phase-shifted second component beam (H2) with second data; a third modulator configured to modulate the third component beam (V1) with third data; a fourth modulator configured to modulate the phase-shifted fourth component beam (V2) with fourth data; a first combiner (840a) configured to combine the data-modulated first component beam (H1) with the data-modulated and phase-shifted second component beam (H2), and output a first data-modulated beam (H'); a second combiner (840b) configured to combine the data-modulated third component beam (V1) with the data-modulated and phase-shifted fourth component beam (V2), and output a second data-modulated beam (V'); and a polarization beam combiner (850) configured to combine the first and second data-modulated beams and output a data beam (342) having two orthogonal polarizations.

4. The optical communication system of claim 1 wherein the receiver comprises:

a receiver splitter having a splitter input and a plurality of splitter outputs, the splitter input receiving the code division multiplexed optical signal comprising K data-modulated code words, and outputting at least K identical received code division multiplexed optical signals each comprising K data-modulated code words; and at least K code receivers, each code receiver having one of said identical received code division multiplexed optical signals input thereto, each code receiver having associated therewith: a receiver pulse spreader configured to create a reference imprinted code beam corresponding to one of the K code words in said received code division multiplexed optical signal; and a receiver unit having an information signal and a reference signal input thereto, wherein the information signal is said one of said identical received code division multiplexed optical signals and the reference signal is the imprinted reference code beam, the receiver unit configured to detect and demodulate said one of the K data-modulated code words to which the reference imprinted code beam corresponds.

5. The optical communication system of claim 4, wherein: the receiver unit comprises an optical detection circuit that receives the information signal and the reference signal, the optical detection circuit configured to output in-phase and quadrature components of a first and a second orthogonal polarization component of the information signal.

6. The optical communication system of claim 5, wherein the receiver unit further comprises a polarization mode dispersion controller configured to: receive digitized in-phase and quadrature components of the first and second orthogonal polarization components of the information signal, and output at least one polarization control signal in response thereto.

7. The optical communication system of claim 6, wherein the at least one polarization control signal is input to a polarization compensator associated with the receiver.

8. The optical communication system of claim 5, wherein the optical detection circuit comprises: a polarization beam splitter configured to receive and split the information signal

into first and second orthogonal polarization components; a first optical phase detector configured to receive the first orthogonal polarization component and the reference signal as inputs, and output in-phase and quadrature components of the first orthogonal polarization component; a second optical phase detector configured to receive the second orthogonal polarization component and the reference signal as inputs, and output in-phase and quadrature components of the second orthogonal polarization component.

9. The optical communication system of claim 8, wherein the optical detection circuit further comprises: a symbol synchronizer circuit receiving said in-phase and quadrature components of the first and second orthogonal polarization components of the information signal, and outputting at least one timing signal to synchronize symbol boundaries of said data-modulated codewords in said optical phase detectors. a variable delay configured to synchronize the first and second orthogonal polarization components, the variable delay receiving a delay signal from the symbol synchronizer circuit.

10. The optical communication system of claim 8, wherein the first and second optical phase detectors each comprise: an optical hybrid detector having first and second signal inputs and first and second signal outputs, the first signal output being proportional an in-phase difference between the first and second signal inputs, and the second signal output being proportional to a quadrature difference between the first and second signal inputs; and a first signal conditioning cascade circuit comprising a first amplifier, a first low pass filter, a first DC bias remover, a first sample and hold, and a first analog-to-digital converter, all arranged to process the first signal output from the optical hybrid detector to thereby form a digitized in-phase component signal; and a second signal conditioning cascade circuit comprising a second amplifier, a second low pass filter, a second DC bias remover, a second sample and hold, and a second analog-to-digital converter, all arranged to process the second signal output from the optical hybrid detector to thereby form a digitized quadrature component signal.

11. The optical communication system of claim 10, wherein the optical hybrid detector having first and second signal inputs comprises: optical circuitry configured to split and phase shift the second signal input to form a first signal (R3) having 0.degree. phase shift, a second signal (R4) having a 90.degree. phase shift, a third signal (R5) having a 180.degree. phase shift and a fourth signal (R6) having a 270.degree. phase shift; first, second, third and fourth combiners, configured to combine a copy of the first signal input with a copy of the second signal input shifted by 0.degree., 90.degree., 180.degree. and 270.degree., respectively, to output first second, third and fourth combined beams, respectively; a first matched detector configured to receive said first and third combined beams and output a first output signal that is proportional to an in-phase difference between the first and second signal inputs; and a second matched detector configured to receive said second and fourth combined beams and output a second output signal that is proportional to quadrature difference between the first and second signal inputs.

12. A pulse spreader configured to accept a code beam comprising a single pulse within a symbol period of length T, and output an imprinted code beam comprising a number P modulated pulses having a length $C=T/P$ chip periods, the pulse spreader comprising: a 1:P splitter configured to split the code beam input thereto into P identical code beams, each code beam having a single pulse; P chip modulators, each chip modulator configured to receive a single pulse and

output a delayed modulated pulse, the p-th chip modulator comprising: a delay circuit configured to delay said single pulse by $(p-1)*C$, where $C=T/P$ is a chip period, p representing an index; and a chip modulation circuit configured to code-modulate the delayed single pulse by a p-th code value belonging to an orthogonal code of length P; and a P:1 combiner configured to combine code-modulated outputs from the P chip modulation circuits into the imprinted code word comprising P pulses within said symbol period T.

13. An optical signal data modulator for modulating an input signal, the optical signal data modulator comprising: optical splitter circuitry configured to split the input signal into identical first (H1), second (H2), third (V1) and fourth (V2) component beams; a first phase shifter configured to impart a 90.degree. phase shift to the second component beam (H2); a second phase shifter configured to impart a 90.degree. phase shift to the fourth component beam (H4); a first modulator configured to modulate the first component beam (H1) with first data; a second modulator configured to modulate the phase-shifted second component beam (H2) with second data; a third modulator configured to modulate the third component beam (V1) with third data; a fourth modulator configured to modulate the phase-shifted fourth component beam (V2) with fourth data; a first combiner (840a) configured to combine the data-modulated first component beam (H1) with the data-modulated and phase-shifted second component beam (H2), and output a first data-modulated beam (H'); a second combiner (840b) configured to combine the data-modulated third component beam (V1) with the data-modulated and phase-shifted fourth component beam (V2), and output a second data-modulated beam (V'); and a polarization beam combiner (850) configured to combine the first and second data-modulated beams and output a data beam (342) having two orthogonal polarizations.

14. The optical signal data modulator of claim 13, wherein the first and second phase shifters and the first, second, third and fourth modulators receive control signals from a power balancer.

15. A code division multiplexed optical signal receiver comprising: a receiver splitter having a splitter input and a plurality of splitter outputs, the splitter input receiving the code division multiplexed optical signal comprising K code words modulated with data, and outputting at least K identical received code division multiplexed optical signals each comprising K data-modulated code words; and at least K code receivers, each code receiver having one of said identical received code division multiplexed optical signals input thereto, each code receiver having associated therewith: a receiver pulse spreader configured to create a reference imprinted code beam corresponding to one of the K code words in said received code division multiplexed optical signal; and a receiver unit having an information signal and a reference signal input thereto, wherein the information signal is said one of said identical received code division multiplexed optical signals and the reference signal is the imprinted reference code beam, the receiver unit configured to detect and demodulate said one of the K data-modulated code words to which the reference imprinted code beam corresponds.

16. An optical phase detector in optical communications system comprising: an optical hybrid detector having first and second signal inputs and first and second signal outputs, the first signal output being proportional to an in-phase difference between the first and second signal inputs, and the second signal output being proportional to a quadrature difference between the first and second signal inputs; and a first signal conditioning cascade circuit comprising a first amplifier, a first low pass filter, a first DC bias remover, a first sample and hold, and a first analog-to-digital converter, all arranged to process the first signal output from the optical hybrid detector to thereby form a digitized in-phase component signal; and a second signal conditioning cascade circuit comprising a second amplifier, a second low pass filter, a second DC bias remover, a second sample and hold, and a second analog-to-digital converter, all arranged to process the second signal output from the optical hybrid detector to thereby form a digitized quadrature component signal.

17. The optical phase detector of claim 16, wherein the optical hybrid detector having first and second signal inputs comprises: optical circuitry configured to split and phase shift the second signal input to form a first signal (R3) having 0.degree. phase shift, a second signal (R4) having a 90.degree. phase shift, a third signal (R5) having a 180.degree. phase shift and a fourth signal (R6) having a 270.degree. phase shift; first, second, third and fourth combiners, configured to combine a copy of the first signal input with a copy of the second signal input shifted by 0.degree., 90.degree., 180.degree. and 270.degree., respectively, to output first, second, third and fourth combined beams, respectively; a first matched detector configured to receive said first and third combined beams and output a first output signal that is proportional to an in-phase difference between the first and second signal inputs; and a second matched detector configured to receive said second and fourth combined beams and output a second output signal that is proportional to quadrature difference between the first and second signal inputs.

18. An optical hybrid detector of claim 16 having first and second signal inputs and comprising: optical circuitry configured to split and phase shift the second signal input to form a first signal (R3) having 0.degree. phase shift, a second signal (R4) having a 90.degree. phase shift, a third signal (R5) having a 180.degree. phase shift and a fourth signal (R6) having a 270.degree. phase shift; first, second, third and fourth combiners, configured to combine a copy of the first signal input with a copy of the second signal input shifted by 0.degree., 90.degree., 180.degree. and 270.degree., respectively, to output first, second, third and fourth combined beams, respectively; a first matched detector configured to receive said first and third combined beams and output a first output signal that is proportional to an in-phase difference between the first and second signal inputs; and a second matched detector configured to receive said second and fourth combined beams and output a second output signal that is proportional to quadrature difference between the first and second signal inputs.