Direct Detection DIfferential Polarization-Phase-Shift Keying for High Spectral Efficiency Optical Communication

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Efficient apparatus, methods, systems and devices to generate, transmit and detect optical differential polarization-phase-shift keying signals are disclosed for high spectral efficiency optical communication systems. It includes an electrical encoder and an optical encoder for generation of differentially encoded polarization-phase modulated optical signals and optical demodulators and balanced detectors for detection of the optical signals. The optical signals are transmitted through optical fiber links or free space. The electrical encoder maps independent data channels into differentially-encoded data sequences. In the optical encoder, the encoded data sequences from the electrical encoder drive optical modulators to generate differentially-encoded polarization-phase modulated optical signals at a symbol rate equal to the bit rate of each input data channel. After transmission through a transmission medium, the optical signals are demodulated optically and the original data are recovered by multilevel detection, without recovering the polarization state of received signals.
Fig. 1

Fig. 2a

Fig. 3a
Fig. 2b

Fig. 3b
Fig. 4

\[ D_{1,k} = d_{1,k} \oplus D_{1,k-1} \]
Electrical Encoder

60°/120° Differential Phase modulator

Fig. 5

Electrical Encoder

1-bit delay

Logic Network

D_{1,k} = d_{1,k} \oplus D_{1,k-1}

D_{2LSB,k} = \overline{d}_{2,k} \& D_{2LSB,k-1} + d_{2,k} \& D_{2LSB,k-1}

D_{2MSB,k} = \overline{d}_{2,k} \& D_{2LSB,k-1} + d_{2,k} \& D_{2MSB,k-1}

Fig. 6
Fig. 7

Fig. 8
Fig. 9

Decision Circuit

Balanced Detectors

Delay Interferometers

Received signal

\[ d_1 \]
\[ d_2 \]
\[ d_3 \]
\[ d_4 \]
$$D_{1,k} = d_{1,k} \oplus (D_{1,k-1} \overline{D_{2,k-1}}) + d_{2,k} \oplus (\overline{D_{1,k-1}} \overline{D_{2,k-1}})$$

$$D_{2,k} = d_{1,k} \oplus (\overline{D_{1,k-1}} \overline{D_{2,k-1}}) + d_{2,k} \oplus (D_{1,k-1} \overline{D_{2,k-1}})$$

Fig. 10
Fig. 12

Optical Demodulators and Detectors

Optical Demodulators and Detectors

Optical Source, Optical Source & Optical Encoder, and Optical Source & Optical Encoder

DPoPSK Electrical Encoder

DPoPSK Electrical Encoder

Mix

Mix
Figure 13
1

DIRECT DETECTION DIFFERENTIAL POLARIZATION-PHASE-SHIFT KEYING FOR HIGH SPECTRAL EFFICIENCY OPTICAL COMMUNICATION

The invention relates to optical data transmission and in particular to systems, devices, apparatus, and methods of generating, distributing, processing and detecting optical signals using differential polarization-phase-shift keying for high spectral efficiency optical communications.

BACKGROUND AND PRIOR ART

High capacity optical transmission systems require high spectral efficiency due to finite bandwidth of optical amplifiers and/or transmission medium (e.g. optical fiber). High spectral efficiency not only leads to larger aggregate capacity but also provides better tolerance to chromatic dispersion and polarization-mode dispersion (PMD). Spectral efficiency of modulation formats can be increased by using multilevel modulation and by encoding information in additional degree of freedoms. A preference for spectral-efficient transmission systems is direct detection to allow simple receiver structures free of local oscillators.

At the optical frequency, polarization is an additional degree of freedom that can be used to carry information. For example, Polarization-Division Multiplexing (PDM) can effectively double spectral efficiency by transmitting two independent channels simultaneously in orthogonal State of Polarizations (SOPs) at the same wavelength. In conventional PDM systems, dynamic polarization control is required at the receiver to track the SOP of the incoming signal because it may not be preserved during transmission. Another highly desired feature is constant intensity. Constant intensity modulation format is more robust against optical nonlinearities in transmission.

SUMMARY OF THE INVENTION

A primary objective of the present invention is to provide efficient apparatus, methods, systems and devices to generate, transmit and detect differential polarization-phase-shift keying (DPolPSK) signals for high spectral efficiency optical communication systems.

A second objective of the apparatus, methods, systems and devices of the present invention is to provide a transmitter and receiver for recovering the original input data, wherein the receiving process is not affected by the slow polarization change during transmission of differentially encoded polarization-phase modulated optical signals.

A third objective of the apparatus, methods, systems and devices of the present invention is to provide high spectral efficiency without polarization control, resulting in improved dispersion tolerance and reduced system cost.

In an embodiment, the system includes a transmitter having an electrical encoder and an optical encoder including polarization beam splitter and beam combiner for generation of DPolPSK optical signals and a receiver including an optical demodulator and balanced detector for detection of the optical signals. The optical signals are transmitted through either optical fiber links or free space.

The electrical encoder maps independent data channels into differentially-encoded data sequences. In the optical encoder, the optical beam is first split into two beams by a polarization beam splitter; each beam is then separately modulated by optical modulators driven by the encoded data sequences from the electrical encoders; after recombining two beams in a polarization beam combiner, the optical beam is differentially encoded in both polarization and phase at a symbol rate equal to the bit rate of each input data channel.

After transmission through the medium such as optical fiber or free space, the optical signals are demodulated optically and the original data are recovered by balanced detectors with multilevel detection. In the optical demodulator, the differentially encoded polarization-phase signals are converted into optical signals with distinct power levels. A further embodiment provides an optical communication method using differential polarization-phase-shift keying for high spectral efficiency wavelength-division multiplexing optical communications. At the transmitter, at least two differentially encoded polarization-phase modulated optical signals with at least two optical carriers with different wavelengths are generated from at least two input data channels and the at least two differentially encoded polarization-phase modulated optical signals are transmitted over an optical transmission medium. At the receiver, the at least two differentially encoded polarization-phase modulated optical signals are decoded to recover the at least two input data channels. The receiving step is not affected by the slow polarization change during transmission of the at least two differentially encoded polarization-phase modulated optical signals.

The optical signal generation step includes electrically encoding at least two input data into the at least two differentially encoded data sequences, generating at least two optical carriers and optically encoding the at least two differentially encoded data sequences, wherein the at least two differentially encoded data sequences drive at least two set of optical modulators to generate at least two differentially encoded polarization-phase modulated optical signals. The receiving step includes optically demodulating said at least two differentially encoded polarization-phase modulated optical signals to generate at least two optical signals with distinct power levels and detecting the at least two optical signals to recover the at least two input data, wherein the optical demodulation and detection steps are not affected by the slow polarization change during transmission of the at least two differentially encoded polarization-phase modulated optical signals.

Further objects and advantages of this invention will be apparent from the following detailed description of the presently preferred embodiments which are illustrated schematically in the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a schematic diagram of the differential polarization-phase-shift keying (DPolPSK) transmission system of the present invention.

FIG. 2a is a schematic diagram of a transmitter for quaternary DPolPSK.

FIG. 2b is a schematic diagram of plural transmitters for quaternary DPolPSK.

FIG. 3a is a schematic diagram of a receiver for quaternary DPolPSK.

FIG. 3b is a schematic diagram of plural receivers for quaternary DPolPSK.

FIG. 4 shows a schematic diagram of an electrical encoder used in FIG. 2 for quaternary DPolPSK.

FIG. 5 shows the second embodiment of a transmitter for quaternary DPolPSK.

FIG. 6 shows a schematic diagram of an electrical encoder used in FIG. 5 for quaternary DPolPSK.
FIG. 7 shows the second embodiment of a receiver for quaternary DPoI-PSK.

FIG. 8 shows a schematic diagram of a transmitter for 16-ary DPoI-PSK.

FIG. 9 shows a schematic diagram of a receiver for 16-ary DPoI-PSK.

FIG. 10 shows a schematic diagram of an electrical encoder used in FIG. 8 for 16-ary DPoI-PSK.

FIG. 11 is a schematic diagram of another embodiment of the differential polarization-phase-shift keying (DPoI-PSK) transmission system.

FIG. 12 is a schematic diagram of the differential polarization-phase-shift keying transmission system of FIG. 11 with plural multiplexers and de-multiplexers.

FIG. 13 is a schematic diagram showing a third embodiment of a transmitter for quaternary DPoI-PSK.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Before explaining the disclosed embodiments of the present invention in detail, it is to be understood that the invention is not limited in its applications to the details of the particular arrangements shown since the invention is capable of other embodiments. Also, the terminology used herein is for the purpose of description and not of limitation.

The following is a list of designators used in the detailed description and figures:

100 system
110 electrical encoder
120 optical source and optical encoder
130 optical demodulators and detectors
140 transmission medium
160 quaternary DPoI-PSK transmitter
210 binary phase modulator
215 binary phase modulator
220 polarized beam splitter
230 polarization beam combiner
240 optical source
245 polarization controller
250 quaternary DPoI-PSK receiver
310 delay interferometer
320 balanced detector
330 decision circuit
340 quaternary DPoI-PSK electrical encoder
410 logic network
415 one-bit delay
420 logic network
425 one-bit delay
500 quaternary DPoI-PSK transmitter
515 phase modulator
545 polarization controller
600 quaternary DPoI-PSK electrical encoder
700 quaternary DPoI-PSK receiver
730 decision circuit
800 16-ary DPoI-PSK transmitter
810 quaternary phase modulator
815 quaternary phase modulator
900 16-ary DPoI-PSK receiver
905 optical splitter
910 delay interferometer
915 delay interferometer
920 balanced detector
925 balanced detector
1000 16-ary DPoI-PSK electrical encoder
1010 logical network
1020 logical network

The apparatus, methods, system and devices of the present invention provide a novel constant intensity modulation format that encodes information both in phase and polarization of lightwave yet without the need to recover the state of polarization (SOP) of lightwave at the receiver. The modulation format is named differential polarization-phase-shift keying (DPoI-PSK). Examples for implementation of the electronic and optical encoding/modulation and detection schemes of DPoI-PSK are disclosed. Examples include the quaternary and 16-ary DPoI-PSK. M-ary DPoI-PSKs other than quaternary and 16-ary are also possible based on the same encoding/modulation and detection schemes.

The polarization-phase symbol in DPoI-PSK can be represented by the Jones-vector. A possible set of Jones-vectors for polarization-phase symbols in a quaternary DPoI-PSK is \{ (1, 2), (-1, 2), (1, -2), (-1, -2) \}. In its quaternary form, each encoded symbol carries two bits of information and the symbol rate is half of the total bit rate. A general schematic view of the DPoI-PSK transmission system is shown in FIG. 1. For the quaternary DPoI-PSK, the indexes of data sequences are limited to 1 and 2. The system comprises an electrical encoder 110 and an optical encoder 120 connected with an optical receiver 130 via optical fiber links or free space 140. The electrical encoder maps two independent data channels, \( d_1 \) and \( d_2 \), into two differentially encoded data sequences, \( D_1 \) and \( D_2 \). In the optical encoder, the encoded data sequences drive optical modulators to generate differentially encoded optical signals at a symbol rate equal to the bit rate of each input data channel. After transmission through optical fiber, the differentially encoded optical signal is demodulated optically and the original data, \( d_1 \) and \( d_2 \), are recovered by multilevel detection.

Four polarization-phase symbols, (1, 2), (-1, 2), (1, -2), and (-1, -2), are generated during the optical encoding. The transmitter uses two parallel optical modulators 210 and 215 between a polarization beam splitter 220 and a polarization beam combiner 230, as shown in FIG. 2. The polarization beam combiner 220 is used to divide the parallel and orthogonal polarization components of the optical source, the semiconductor laser 240 in this example. The polarization state of optical source 240 may be adjusted by a polarization controller 245 to achieve a predefined power splitting ratio, say 1:2 for this example, between the parallel and orthogonal polarization states.

Each polarization state is then independently modulated by a \([0°, 180°]\) binary phase modulator such as a Mach-Zehnder (MZ) modulator biased at the transmission null with a 2V, peak-to-peak voltage, driven by the encoded outputs of electrical encoders, \( D_1 \) and \( D_2 \), respectively. The two phase-modulated signals residing in the orthogonal polarization states are combined by the polarization beam combiner to generate polarization-phase symbols, (1, 2), (-1, 2), (1, -2), and (-1, -2). An additional pulse carver may be used before or after modulators for return-to-zero pulse shaping as shown in FIG. 13.

The receiver receiving the optical DPoI-PSK signals uses an optical one-bit delayed interferometer 310 and a balanced detector 320 as shown in FIG. 3. In the one-bit delayed interferometer 310, the differentially encoded DPoI-PSK signal is converted into an optical signal with distinct power levels. In this example, four distinct levels are generated. A detector with decision circuit detects the optical signal at the output of optical demodulator and recovers the original input data \( d_1 \) and \( d_2 \). In the balanced detector 320, the multilevel decision circuit is a four-level slicer 330 in the example shown. Gray code may be used to avoid two bit errors generated by one symbol error and a possible Gray-code constellation four levels is shown in FIG. 3.

An important feature of the present demodulating technique is that the demodulation and detection process is essen-
transmission. The relative polarization between two adjacent
the same. An additional
ation. The phase offsets in two interferometers are
d 1 and d 2 , into two differentially-encoded data
nels, d 1 and d 2 , into two differentially-encoded data
quences, D 1 and D 2 , to exactly recover the original binary
put data sequences with the optical encoding and demodu-
olution scheme defined above. A schematic diagram of the
electrical encoder 400 is shown in FIG. 4, where the logic
D 1,k-1 , in which the subscript k denotes the k-th bit in the data
sequence. The two logic networks 410 and 420 in FIG. 4 are
the same. An additional XOR logic operation, d, @
d k is required if Gray code is used in FIG. 3. The XOR
operation can be removed if a simple 10, 11, 01, 00
onstellation instead of 10, 11, 01, 00 is used in FIG. 3.

The optical demodulator shown in FIG. 3 and the
ceeding electrical encoder shown in FIG. 4 include a one-bit
elay in the delay interferometer 310 and 1-bit delay
back 415 and 425 to the logic network 410 and 420, respec-
tively. However, the amount of delay is not limited to one-bit.
For example, the DPolPSK transmission system is still ef-
tive provided that the amount of delay in both the electrical
encoder and the demodulator are two-bit.

Another embodiment of the quaternary DPolPSK optical
encoder is shown in FIG. 5. In contrast to FIG. 2, the power
plitting ratio in this embodiment is 1:1 by adjusting polar-
zation controller 545. The phase modulator 515 in the lower
arm is a \{0°, 60°, 120°, 180°\} 4-level phase modulator,
stead of a binary phase modulator 215 shown in FIG. 2.
This modulator 515 is used to generate a \{60°, 120°\} differ-
tial phase modulated optical signal. The corresponding electrical
encoder 600 is shown in FIG. 6, where D 2 has two digits: LSBS
and MSBS denoting least significant bit and most significant
bit, respectively. The optical demodulator and receiver corre-
sponding to this embodiment is shown in FIG. 7. In compar-
ison with FIG. 3, a simple 11, 10, 01, 00 constellation is used
at the slicer 730.

Another example of DPolPSK is the 16-ary DPolPSK. A
possible set of Jones-vectors for polarization-phase symbols
in a 16-ary DPolPSK is \{(x 1, z 2 ), (z 1, x 2 ), (x 1, y 2 ) and
(z 1, y 2 )\}. Here, each encoded symbol carries four bits of
information. The schematic view of the 16-ary DPolPSK
transmission system is shown in FIG. 1 with data sequence
indices extending from 1 to 4. A schematic diagram of 16-ary
DPolPSK transmitter 800 is shown in FIG. 8. Compared to
quaternary DPolPSK transmitter 200 shown in FIG. 2, the
binary phase modulators 210 and 215 are replaced by qua-
ternary phase modulators 810 and 815. An implementation of
quaternary phase modulator includes a Mach-Zehnder in-
erferometer with a modulator in each arm. The phase offset
between two arms of interferometer is set to \pi/2. Each modu-
lator is a Mach-Zehnder (MZ) modulator biased at the trans-
mission null with a 2V, peak-to-peak voltage, driven by the
encoded output of electrical encoders.

A schematic diagram of 16-ary DPolPSK receiver is shown
in FIG. 9. After the optical splitter 905, two one-bit delayed
interferometers 910 and 915 are used for optical demodu-
lation. The phase offsets in two interferometers are \pi/4 and
\pm \pi/4, respectively. Two balanced detectors 920 and 925 with
multilevel decision circuit recover the original data sequences
d 1, d 2, d 3 and d 4. In FIG. 9, Gray code is used. An electrical
encoder 1000 for 16-ary DPolPSK is shown in FIG. 10. The
logic network corresponding to the above described optical
encoder is D 1,k-d 1,k @
(D 1,k-1 D 2,k-1 )+d 2,k @
(D 1,k-1 D 2,k-1 )+d 2,k @
(D 1,k-1 D 2,k-1 )+d 2,k @
(D 1,k-1 D 2,k-1 )+d 2,k @
(d 1,k @
and d 2,k @
d k are required if Gray code is used.

In summary, the present invention provides a differential
polarization-phase-shift keying optical communication sys-
tem that includes a transmitter to generate a differentially
coded polarization-phase modulated optical signal from
input data, an optical transmission medium and a receiver for
optically demodulating and detecting the differentially
coded polarization-phase modulated optical signal to
recover the input data. The transmitter includes an electrical
encoder for mapping at least two data channels into at least
two differentially encoded data sequences, an optical source
to provide an optical carrier and an optical encoder for receiv-
ing the optical carrier and the at least two differentially
encoded data sequences to generate the differentially
coded polarization-phase modulated optical signal. The
system can include an optical modulator for return-to-zero
pulse carving before optical modulation of the encoded signal
or an optical modulator for return-to-zero pulse carving after
optical modulation of the encoded signal. In an embodiment,
the system includes a modulator to combine the differentially
coded polarization-phase modulated optical signals into a
wavelength-division multiplexed signal and a demulti-
plexer to separate the wavelength-division multiplexed signal
into the differentially encoded polarization-phase modulated
optical signal as shown in FIGS. 11 and 12.

In the embodiment shown in FIGS. 2b and 3b show a
differential polarization-phase-shift keying optical commu-
nication system including plural transmitters to generate plu-
ral differentially encoded polarization-phase modulated optical
signals from input data, plural optical transmission mediums
for transmitting the plural differentially encoded polarization-phase modulated optical signals and plural
receivers for optically demodulating and detecting the plural
differentially encoded polarization-phase modulated optical
signal to recover the input data. The system can include one or
more multiplexers to combine the plural differentially
coded polarization-phase modulated optical signals into
plural wavelength-division multiplexed signals and one or
more demultiplexers to separate the plural wavelength-divi-
sion multiplexed signals into the plural differentially encoded
polarization-phase modulated optical signals as shown in
FIG. 11 and FIG. 12.

While the invention has been described, disclosed, illus-
trated and shown in various terms of certain embodiments or
modifications which it has presumed in practice, the scope of
the invention is not intended to be, nor should it be deemed to
be, limited thereby and such other modifications or embodi-
ments as may be suggested by the teachings herein are par-
sactively reserved especially as they fall within the breadth
and scope of the claims here appended.
We claim:

1. A differential polarization-phase-shift keying optical communication system comprising:
   a transmitter to generate a differentially encoded polarization-phase modulated optical signal from input data, the transmitter consisting essentially of:
   an electrical encoder for mapping at least two data channels into at least two differentially encoded data sequences, wherein the electrical encoder comprises:
   an encoder for encoding two synchronous binary input data streams into at least two encoded data streams, wherein each said input data stream having a single bit period T between successive data bits;
   a first time delay circuit for delaying D1,k by a period T to produce a first time-delayed encoded signal D1,k-1;
   a first optical phase modulator to modulate the first polarization component of the optical source driven by one of the at least two differentially encoded data sequences with an output phase difference of 0 or \( \pi \); and
   a logic circuit for producing encoded signals D1 and D2 according to the logical relationships
   \[ D_{1,k-1} = -D_{1,k} \]
   \[ D_{2,k} = -D_{2,k-1} \]
   an optical source to provide an optical carrier, and
   an optical encoder for receiving the optical carrier and the at least two differentially encoded data sequences to generate the differentially encoded polarization-phase modulated optical signal; an optical transmission medium; and
   a receiver for optically demodulating and detecting the differentially encoded polarization-phase modulated optical signal to recover the input data in the differential polarization-phase-shift keying optical communication system.

2. The system of claim 1, wherein the optical encoder comprises:
   a first polarization element to separate a first and a second polarization component of the optical source; at least two optical modulators connected in parallel for modulating the first and a second polarization component with the at least two differentially encoded data sequences to produce at least two phase-modulated signals; and
   a second polarization element for combining the at least two phase-modulated signals to generate the differentially encoded polarization-phase modulated optical signal.

3. The system of claim 2, wherein the optical encoder comprises:
   a first optical phase modulator to modulate the first polarization component of the optical source driven by one of the at least two differentially encoded data sequences with an output phase difference of 0 or \( \pi \); and
   a second optical phase modulator to modulate the second polarization component of the optical source driven by one of the at least two differentially encoded data sequences with an output phase difference of 0 or \( \pi \); and

4. The system of claim 2, wherein the optical encoder comprises:
   a second optical phase modulator to modulate the second polarization component of the optical source driven by one of the at least two differentially encoded data sequences with an output phase difference of \( \pi /2 \) or \( -\pi /2 \); and
   a second optical phase modulator to modulate the second polarization component of the optical source driven by the at least two differentially encoded data sequences with an output phase difference of 0, \( \pi /2 \), \( \pi \), or \( 3\pi /2 \); and

5. The system of claim 2, wherein the optical encoder comprises:
   a first optical phase modulator to modulate the first polarization component of the optical source driven by the at least two differentially encoded data sequences with an output phase difference of 0, \( \pi /2 \), \( \pi \), or \( 3\pi /2 \); and
   a second optical phase modulator to modulate the second polarization component of the optical source driven by the at least two differentially encoded data sequences with an output phase difference of 0, \( \pi /2 \), \( \pi \), or \( 3\pi /2 \).

6. The system of claim 2, wherein the differentially encoded polarization-phase modulated signal comprises:
   a polarization-phase symbol of (1, \( J2 \)), (1, \( -J2 \)), (1, \( -J2 \)) and (1, \( J2 \)), and (1, \( -J2 \)).

7. The system of claim 2, wherein the differentially encoded polarization-phase modulated signal comprises:
   a polarization-phase symbol of (1, \( J2 \)), (1, \( -J2 \)), (1, \( -J2 \)), (1, \( J2 \)), (1, \( J2 \)), (1, \( J2 \)).

8. The system of claim 2, wherein the optical encoder further comprises:
   a polarization controller for adjusting a power splitting ratio between the first and a second polarization component of the optical source.

9. The system of claim 8, wherein the power splitting ratio comprises:
   a power splitting ratio of 1:2.

10. The system of claim 8, wherein the power splitting ratio comprises:
   a power splitting ratio of 1:1.

11. The system of claim 1, wherein said receiver comprises:
   an optical power splitter for splitting the differentially encoded polarization-phase modulated optical signal; an optical demodulator for optically demodulating the differentially encoded polarization-phase modulated optical signal; and
   an optical detector for receiving the optically demodulated signal for recovering the input data.

12. The system of claim 11, wherein the optical demodulator comprises:
   a delayed Mach-Zehnder interferometer with a phase shift between two arms of the interferometer to convert said polarization-phase modulated signal into an optical signal with distinct power levels.

13. The system of claim 11, wherein the optical detector comprises:
   a photodetector to convert said optical demodulated signal into an electrical signal having an amplitude that represents said distinct power levels; and
   a decision circuit to process said electrical signal to recover the binary sequences based on said amplitude of the electrical signal.

14. The system of claim 1 further comprising:
   an optical modulator for return-to-zero pulse carving before optical modulation of the encoded signal.

15. The system of claim 1 further comprising:
   an optical modulator for return-to-zero pulse carving after optical modulation of the encoded signal.

16. The system of claim 1 further comprising:
   a multiplexer to combine the differentially encoded polarization-phase modulated optical signals into a wavelength-division-multiplexed signal.
The system of claim 16 further comprising:

17. A demultiplexer to separate the wavelength-division multiplexed signal into the differentially encoded polarization-phase modulated optical signal.

18. The system of claims 1 wherein the differential polarization-phase-shift keying optical communication system comprises:


20. The system of claims 1 wherein the differential polarization-phase-shift keying optical communication system comprises:


20. An optical communication method using differential polarization-phase-shift keying for high spectral efficiency optical communication, the method comprising the steps of:

20. Generating at least two differentially encoded polarization-phase modulated optical signals over an optical transmission medium; and

20. Receiving the at least two differentially encoded polarization-phase modulated optical signals to recover the at least two input data channels; wherein the receiving step is not affected by the slow polarization change during transmission of the at least two differentially encoded polarization-phase modulated optical signals, wherein the optical signal generation step comprises the steps of:

20. Electrically encoding at least two input data channels into at least two differentially encoded data sequences by an electrical encoder, wherein the electrical encoder comprises:

20. An encoder for encoding four synchronous binary input data streams $d_1$, $d_2$, $d_3$ and $d_4$ into four encoded data streams $D_1$, $D_2$, $D_3$ and $D_4$, each said input data stream having a single bit period $T$ between successive data bits;

20. A first time delay circuit for delaying $D_1$ by a period $T$ to produce a first time-delayed encoded signal $D_{1,k}$;

20. A second time delay circuit for delaying $D_2$ by a period $T$ to produce a second time-delayed encoded signal $D_{2,k}$;

20. A third time delay circuit for delaying $D_3$ by a period $T$ to produce a third time-delayed encoded signal $D_{3,k}$;

20. A fourth time delay circuit for delaying $D_4$ by a period $T$ to produce a fourth time-delayed encoded signal $D_{4,k}$; and

20. A logic circuit for producing encoded signals $D_1$, $D_2$, $D_3$ and $D_4$ according to the logical relationships:

20. $D_{1,k} = d_1$; $D_{2,k} = d_2$; $D_{3,k} = d_3$; $D_{4,k} = d_4$.

20. The method of claim 20, wherein the receiving step comprises the steps of:

20. Optically demodulating said at least two differentially encoded polarization-phase modulated optical signals to generate at least two optical signals with distinct power levels; and

20. Detecting the at least two optical signals to recover the at least two input data, wherein the optical demodulation and detection steps are not affected by the slow polarization change during transmission of the at least two differentially encoded polarization-phase modulated optical signals.

22. A differential polarization-phase-shift keying optical communication system comprising:

22. A plurality of transmitters to generate a plurality of differentially encoded polarization-phase modulated optical signals from input data, each one of the plurality of transmitters including:

22. An encoder for mapping at least two data channels into at least two differentially encoded data sequences, wherein the encoder comprises:

22. A time delay circuit for delaying $D_1$ by a period $T$ to produce a first time-delayed encoded signal $D_{1,k}$;

22. A second time delay circuit for delaying $D_2$ by a period $T$ to produce a second time-delayed encoded signal $D_{2,k}$;

22. A third time delay circuit for delaying $D_3$ by a period $T$ to produce a third time-delayed encoded signal $D_{3,k}$; and

22. A fourth time delay circuit for delaying $D_4$ by a period $T$ to produce a fourth time-delayed encoded signal $D_{4,k}$; and

22. An optical source to provide an optical carrier; and

22. A plurality of transmitters to generate a plurality of differentially encoded polarization-phase modulated optical signals from input data, each one of the plurality of transmitters including:

22. An encoder for mapping at least two data channels into at least two differentially encoded data sequences, wherein the encoder comprises:

22. A time delay circuit for delaying $D_1$ by a period $T$ to produce a first time-delayed encoded signal $D_{1,k}$;

22. A second time delay circuit for delaying $D_2$ by a period $T$ to produce a second time-delayed encoded signal $D_{2,k}$;

22. A third time delay circuit for delaying $D_3$ by a period $T$ to produce a third time-delayed encoded signal $D_{3,k}$; and

22. A fourth time delay circuit for delaying $D_4$ by a period $T$ to produce a fourth time-delayed encoded signal $D_{4,k}$; and

22. A logic circuit for producing encoded signals $D_1$, $D_2$, $D_3$ and $D_4$ according to the logical relationships:

22. $D_{1,k} = d_1$; $D_{2,k} = d_2$; $D_{3,k} = d_3$; $D_{4,k} = d_4$.

22. The method of claim 22, wherein the receiving step comprises the steps of:

22. Optically demodulating said at least two differentially encoded polarization-phase modulated optical signals to generate at least two optical signals with distinct power levels; and

22. Detecting the at least two optical signals to recover the at least two input data, wherein the optical demodulation and detection steps are not affected by the slow polarization change during transmission of the at least two differentially encoded polarization-phase modulated optical signals.
23. The system of claim 22 further comprising: plural demultiplexers to separate the plural differentially 
educed polarization-phase modulated optical signals into plural wavelength-division multiplexed signals.

24. The system of claim 23 further comprising: plural demultiplexers to separate the plural wavelength-division multiplexed signals into the plural differentially encoded polarization-phase modulated optical signals.

25. A differential polarization-phase-shift keying optical communication system comprising:
a transmitter to generate a differentially encoded polarization-phase modulated optical signal from input data, the transmitter consisting essentially of:
an electrical encoder for mapping at least two data channels into at least two differentially encoded data sequences, wherein the electrical encoder comprises:
an encoder for encoding two synchronous binary input data streams d1 and d2 into two encoded data streams D1 and D2, each said input data stream having a single bit period T between successive data bits;
a first time delay circuit for delaying D1 by a period T to produce a first time-delayed encoded signal D1.k-1; a second time delay circuit for delaying D2 by a period T to produce a second time-delayed encoded signal D2.k-1; and
a logic circuit for producing encoded signals D1 and D2, where D2 has two digits, D2LSB and D2MSB, according to the logical relationships

\[ D1.k = d1 \]  
\[ D2LSB,k = a2,k \]  
\[ D2MSB,k = n2LSB,k-1 + d2,k \]

\[ D1.k-1 \times D2LSB,k \times D2MSB,k-1 \]

an optical source to provide an optical carrier, and
an optical encoder for receiving the optical carrier and the at least two differentially encoded data sequences to generate the differentially encoded polarization-phase modulated optical signal;
an optical transmission medium; and
a receiver for optically demodulating and detecting the differentially encoded polarization-phase modulated optical signal to recover the input data in the differential polarization-phase-shift keying optical communication system.

26. The system of claim 25, wherein the optical encoder comprises:
a first polarization element to separate a first and a second polarization component of the optical source; at least two optical modulators connected in parallel for modulating the first and a second polarization component with the at least two differentially encoded data sequences to produce at least two phase-modulated signals; and

27. A differential polarization-phase-shift keying optical communication system comprising:
a transmitter to generate a differentially encoded polarization-phase modulated optical signal from input data, the transmitter consisting essentially of:
an electrical encoder for mapping at least two data channels into at least two differentially encoded data sequences, the electrical encoded comprising:
an encoder for encoding four synchronous binary input data streams d1, d2, d3 and d4 into four encoded data streams D1, D2, D3 and D4, each said input data stream having a single bit period T between successive data bits; a first time delay circuit for delaying D1 by a period T to produce a first time-delayed encoded signal D1.k-1; a second time delay circuit for delaying D2 by a period T to produce a second time-delayed encoded signal D2.k-1; a third time delay circuit for delaying D3 by a period T to produce a third time-delayed encoded signal D3.k-1; and
a fourth time delay circuit for delaying D4 by a period T to produce a fourth time-delayed encoded signal D4.k-1; and
a logic circuit for producing encoded signals D1, D2, D3 and D4 according to the logical relationships:

\[ D3.k = d3 \]
\[ D4.k = d4 \]
\[ D1.k-1 \times D2LSB,k \times D2MSB,k-1 \]
\[ D1,k-1 \times D2LSB,k \times D2MSB,k-1 \]

an optical source to provide an optical carrier; and
an optical encoder for receiving the optical carrier and the at least two differentially encoded data sequences to generate the differentially encoded polarization-phase modulated optical signal;
an optical transmission medium; and
a receiver for optically demodulating and detecting the differentially encoded polarization-phase modulated optical signal to recover the input data in the differential polarization-phase-shift keying optical communication system.