

QUANTUM KEY DISTRIBUTION FREE SPACE OPTICAL COMMUNICATION

TECHNOLOGICAL FIELD

The present invention is generally in the field of quantum key distribution (QKD) particularly over free space medium.

5 BACKGROUND ART

References considered to be relevant as background to the presently disclosed subject matter are listed below:

- [1] D. Scalcon *et al* "*Cross-encoded quantum key distribution exploiting time-bin and polarization states with qubit-based synchronization*", arXiv:2111.13383 (2021).
- 10 [2] C. Agnesi *et al* "*All-fiber self-compensating polarization encoder for quantum key distribution*", Optics Letters Vol. 44, Issue 10, pp. 2398-2401 (2019).
- [3] C. Kupchak *et al* "*Time-bin-to-polarization conversion of ultrafast photonic qubits*" , Phys. Rev. A 96, 053812 (2017).
- [4] J. S. Hodges *et al* "*Polarization/Time-bin basis conversion of entangled photons*",
15 Conference on Lasers and Electro-Optics, CLEO Technical Digest OSA (2012).
- [5] T. Darras *et al* "*A quantum-bit encoding converter*", arXiv:2211.10457 (2022).

BACKGROUND

QKD is gaining considerable recognition for its ability to securely generate secret cryptographic keys between distant parties, guaranteeing that the cryptographic keys thereby
20 generated cannot be intercepted or tampered with, based on principles of quantum mechanics. The cryptographic keys generated by QKD systems can be used for symmetric key cryptography in applications demanding high levels of privacy and long-term secrecy. In typical QKD systems, a secret cryptography key is securely generated between two distant parties, usually referred to as "Alice" (the QKD transmitter) and "Bob" (the QKD receiver), by
25 encoding information as quantum states of single photons, also known as qubits. QKD implementations exploit certain properties of these quantum states to ensure its security, guaranteeing that any attempt to eavesdrop/tap the quantum communication channel will introduce detectable errors into the key generation process indicative of the eavesdropping attempt.

QKD systems can be implemented using various photonic degrees of freedom (DOF), such as polarization, time-bin, and orbital angular momentum, over optical fiber, free-space and satellite links. Two degrees of freedom commonly used in QKD systems are time-bin and phase (between the time-bins) photon state encoding, and polarization photon state encoding.

5 Time-bin phase state photon encoding (T-P) is commonly used in optical fibers based QKD implementations, and the polarization state photon encoding is commonly used in free space optics (FSO) QKD implementations. This is mainly because information is easily encoded in time-bin phase state of photons, and well preserved when propagating along optical fibers, whereas polarization states encoding tends to get mixed along the optical fibers. In free space
10 optics, on the other hand, polarization states encoding is the more robust DOF, since phase states encodings are less robust to atmospheric effects, whereas wave fronts of time bin phase state photon encoding waves are easily distorted, which results in information corruption.. Polarization optics (*e.g.*, Pockels cells) however have a limited bandwidth for information encoding (below 1GHz, compared to phase and amplitude modulation rates that can exceed
15 10GHz). Both active and passive polarization optics have a larger footprint, and are harder to manufacture and align.

In time bin phase state photon encoding techniques, a single photon (or less on average) is typically divided into two separated pulses (referred to herein as time-bins P_0 and P_τ) with quantum information encoded as relative phase and/or intensity difference therebetween. In
20 polarization state photon encoding techniques quantum information is encoded utilizing two basic orthogonal degrees of polarization states of a single photon *e.g.*, horizontal polarization $|H\rangle$ and vertical polarization $|V\rangle$.

Russian Patent Publication No. RU2771775 discloses a method and apparatus for quantum key distribution (QKD) supplementing the QKD apparatus with additional modules
25 ensuring conversion of polarization encoding into phase-time encoding in the transmitter and reverse conversion from phase-time encoding to polarization encoding in the receiver.

Japanese Patent Publication No. JP2008160368 discloses polarization beam splitters used to divide an optical pulse signal resulting from coding quantum information to polarization degrees of freedom of single photons, into two optical pulse signals having a time
30 difference in accordance with polarization, and polarization of one optical pulse signal is rotated by a polarization rotator controlled by a modulation controller, whereby quantum information coded to polarization degrees of freedom is transferred to time degrees of freedom of pulses. Thereafter, the quantum information is transmitted as two divided optical pulse

signals by fibers and is restored into information coded to polarization degrees of freedom in a transmission destination in accordance with reverse procedures.

International Patent Publication No. WO2018214888 discloses polarization and phase entangled coding method and apparatus, and a quantum key distribution system. The method
5 comprises converting a first photon in a polarization entangled photon pair generated by a polarization entangled light source from using polarization coding to using phase coding, and forming the first photon converted to use phase coding and a second photon in the polarization entangled photon pair into a polarization and phase entangled photon pair. The quantum key distribution system based on the polarization and phase entangled coding apparatus can make
10 full use of transmission advantages of different coding schemes over different channels to enable conversion of a photon from using polarization coding to using phase coding when transmissions are performed over different channels.

Chinese Patent Publication No. CN113810191 discloses a quantum key distribution system wherein at the Alice end a single photon is divided into two orthogonal phase equal
15 polarization components through a 1st polarization beam splitter, phase modulation is carried out on the vertical polarization components, then beam combination is carried out through a 2nd polarization beam splitter, and then the polarization components are converted into a left-hand circular polarization component and a right-hand circular polarization component through the 1/4 slide, and at the Bob end the polarization component is changed into a vertical
20 polarization component and a horizontal polarization component again through the 1/4 slide, the recovered horizontal polarization component is subjected to phase modulation, and then phase information is converted into polarization information after beam combination through a 4th polarization beam splitter.

US Patent Publication No. US8509446 discloses QKD free space and fiber network
25 systems that generate a couple of photons which have different wavelength, and input each of the photons into an asymmetric Mach-Zehnder interferometer to obtain time-bin entangled states to provides polarization information with one part of the photons.

European Patent Publication No. EP3742664 discloses a QKD system comprising an emitter adapted to generate a QKD free-space signal, a transmitter station adapted to receive
30 the free-space signal from the emitter, and a remote QKD receiving station supporting a QKD receiver located at a different location than the transmitter station, wherein the transmitter station is adapted to receive said free space signal from the emitter and to forward said signal through a fiber link to the QKD receiver in said remote QKD receiving station.

GENERAL DESCRIPTION

Embodiments hereof are configured to use time-bin phase state qubit (T-P) encoding in QKD systems with additional optical elements configured to convert the time-bin phase state encoded photons into hybrid time-bin and polarization state encoded photons, or pure polarization states, with a simple, compact and manufacturable design. Similarly, in possible
5 embodiments, additional optical elements can be used to convert the hybrid time-bin and polarization state encoded photons or pure polarization states encoded photons, into T-P encoding *e.g.*, for extracting the information encoded therein. The disclosed embodiments can be advantageously exploited for QKD network implementations.

10 Embodiments hereof can be exploited for separating between secure and insecure components of FSO based QKD systems, for allowing placement of qubit signaling equipment in a remote insecure site (*e.g.*, telecommunication tower, building roofs, or suchlike), and placement of sensitive components (also referred to herein as secured units *e.g.*, cryptographic key generation and communication units) of the system in well secured communication centers
15 (*e.g.*, safeguarded/underground facilities, building basement, or suchlike). In such embodiments, the secure cryptographic key generation data/signals, and/or other secured communication, can be communicated with the qubit signaling equipment mounted at the remote insecure site over optical fiber(s). In preferred embodiments the qubit signaling equipment is configured for FSO communication with other QKD system(s) over free space
20 medium *e.g.*, as terrestrial communication between different cities, different country/city regions, between different countries, or over uplink satellite, downlink satellite, or intersatellite communication links.

Accordingly, in embodiments hereof, there is no need for the qubit (*e.g.*, FSO) signaling equipment to be a trusted node, which can be thus mounted at any suitable locations providing
25 the required signal communication coverage *e.g.*, at further remote and/or elevated location, thereby avoiding the extra complexity that a trusted node entails, and enhancing the quality and performance of the quantum communication link.

The communication between the secured units of the system and its FSO communication system is preferably carried out over the optical fiber(s) utilizing time bin phase state (T-P) photon encoding, and the communication between the FSO communication systems
30 of the different QKD systems is carried out over the free space medium utilizing the hybrid time-bin and polarization state photon encoding, such as disclosed herein. In QKD transmitters of embodiments hereof, the FSO communication system can be configured to convert the T-P

encoded photons thereby received into time-bin and polarization state photons suitable for quantum communication over the free space medium. Similarly, in QKD receivers of embodiments hereof, the FSO communication system can be configured to convert the hybrid time-bin and polarization state encoded photons thereby received into T-P encoded photons
5 suitable for communication with its secured units over optical fiber(s).

In some embodiments the secured units of the QKD transmitter and/or of the QKD receiver are located in a well secured location, and their FSO communication systems can be installed at a separate relatively insecure location. In addition, in applications wherein there is no need for separation between the QKD transmitter/receiver from the FSO communication
10 system there is an advantage for the conversion of the T-P encoded photons into the hybrid time-bin and polarization state encoded photons. For example, in satellite applications, where low volume and low power are of high importance, the fiber-based transmitter designs suggested below provide a significant advantage, as it allows mechanical design flexibility due to the ease of routing optical fibers, low power consumption since telecom components are
15 typically readily optimized in power consumption, and a robust design since less opto-mechanical and electro-mechanical modules are required.

A T-P to hybrid time-bin and polarization state photon encoding (T2H) converter is used in some embodiments in the FSO communication system of the QKD transmitter. The T2H converter can be configured to utilize an imbalanced (*e.g.*, Mach Zehnder or Michelson
20 interferometer with Faraday mirrors having short and long arms) interferometer for producing at least three observable (*e.g.*, time separated) signal patterns for the polarization state photon encoding thereby produced. A beam combiner can be used in the imbalanced interferometer to combine the optical signals propagating along its short and long arms. The beam combiner can be configured to split (*e.g.*, 50:50, or other suitable ratio) the combined optical signals emerging
25 from the imbalanced interferometer into two separate optical fiber polarizing arms configured to apply the polarization state photon encoding.

For example, a horizontally oriented ($| \leftrightarrow \rangle$) polarizer can be used in one of the optical fiber polarizing arms for transmitting therefrom horizontally polarized optical signals, and a vertically oriented ($| \updownarrow \rangle$) polarizer can be used in the other optical fiber polarizing arm for
30 transmitting therefrom vertically polarized optical signals. In possible embodiments at least one $\lambda/2$ phase retarder is used in at least one of the optical fiber polarizing arms to affect the desired polarization states to the optical signals emerging from the imbalanced interferometer.

A beam combiner can be used to combine the optical signals emerging from the optical fiber polarization arms and thereby produce hybrid time-bin and polarization state encoded

photons. Optionally, but in some embodiments preferably, the beam combiner is configured to split the hybrid time-bin and polarization state encoded photons thereby produced into at least two light output components *e.g.*, output optical fibers. At least one of the light output components can be used as an output of the T2H converter *e.g.*, optically coupled to the FSO transmitter. At least another one of the light output components from the beam combiner can be used for monitoring (*e.g.*, by a state characterization system, which can includes polarization optics and photodiodes) the hybrid time-bin and polarization state encoded photons produced by the T2H converter. In possible embodiments an attenuator is used (*e.g.*, in the T2H converter or at its output) to attenuate the transmitted signal to a single photon level, as required in QKD applications. The monitoring of the light output components from the beam combiner, however, preferably operates over higher intensities, and thus does not require single photon detectors.

In other possible embodiments at least one $\lambda/2$ phase retarder is used in the long (and/or short) arm of the imbalanced interferometer to affect the photon polarization states. In such possible embodiments there may be no need for the optical fiber polarizing arms. Particularly, the beam combiner of the imbalanced interferometer can be configured to split the combined optical signals of the imbalanced interferometer into the at least two (*e.g.*, 50:50, or other suitable ratio) light output components. At least one of the light output components from the beam combiner of the imbalanced interferometer can be used as an output of the T2H converter *e.g.*, optically coupled to the FSO transmitter. At least another one of the light output components from the beam combiner of the imbalanced interferometer can be used for monitoring (*e.g.*, by a state characterization system, which can includes polarization optics and photodiodes) the hybrid time-bin and polarization state photons produced by the T2H converter. In possible embodiments an attenuator is used (*e.g.*, in the T2H converter or at its output) to attenuate the transmitted signal to a single photon level, , as required in QKD applications. The monitoring of the light output components from the beam combiner, however, preferably operates over higher intensities, and thus does not require single photon detectors.

In some embodiments the imbalanced interferometer of the T2H converter is configured to covert each T-P state encoded photon thereby received into three distinguishable optical pulse signals, wherein the first optical pulse signal is generated responsive to passage of the first time-bin (P_0) of the T-P state encoded photon through the short arm of the imbalanced interferometer, the second optical pulse signal is generated responsive to an interference pattern of the first and second time-bins (P_0, P_τ) of the T-P state encoded photon after they respectively

pass through the long and short arms of the imbalanced interferometer, and the third optical pulse signal is generated responsive to passage the second time-bin (P_t) of the T-P state encoded photon through the long arm of the imbalanced interferometer.

5 A hybrid time-bin and polarization to T-P state photon encoding (H2T) converter is used in some embodiments in the FSO communication system of the QKD receiver. The H2T converter can be configured according to implementations disclosed in the above-mentioned patent publications and/or reference [1].

10 Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention pertains. Although methods and optical elements similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and optical elements are described below. In case of conflict, the specification, including definitions, will control. In addition, the optical elements, methods, and examples are illustrative only and not intended to be limiting.

15 The interferometer of some embodiments disclosed herein are implemented such that the optical signals propagating through their arms (when in orthogonal polarization orientations) are combined without interference.

One inventive aspect of the subject matter disclosed herein relates to a photon state polarization converter comprising: an imbalanced interferometer configured to generate the
20 following three optical signal pulses responsive to time-bin and phase states encoded photons thereby received: (i) a first optical pulse signal responsive to a first time-bin of the time-bin and phase states encoded photon emerging through a short arm of the imbalanced interferometer; (ii) a second optical pulse signal responsive to an interference pattern between said first time-bin emerging through a long arm of the imbalanced interferometer and a second
25 time-bin of the time-bin and phase states encoded photon emerging through the short arm; and (iii) a third optical pulse signal responsive to the second time-bin emerging through the long arm of the imbalanced interferometer; and at least one polarization orientation manipulating device configured to affect orthogonal polarization orientations to light components from the imbalanced interferometer and thereby generate hybrid time-bin and polarization states
30 encoded photons.

The photon state polarization converter comprising in some embodiments two polarization arms optically coupled to the imbalanced interferometer and configured for generating the two orthogonally polarized optical signals. Each one of the polarization arms

can comprise a respective polarization orientation manipulating device. The photon state polarization converter can comprise a half wavelength phase retarder in one of the polarization arms.

5 The time-bin and phase states encoded photons can have a defined linear polarization orientation. In this case the photon state polarization converter can comprise a half wavelength phase retarder in one of the arms of the imbalanced interferometer.

10 The time-bin and phase states encoded photons can have a defined diagonal polarization orientation. In this case the photon state polarization converter can comprise a half wavelength phase retarder in one of the arms of the imbalanced interferometer and a polarizing beam splitter for transmitting the time-bin and phase states encoded photons into the long and short arms of the imbalanced interferometer.

15 The time-bin and phase states encoded photons can have a defined linear polarization orientation. In this case the photon state polarization converter can comprise a half wavelength phase retarder in one of the arms of the imbalanced interferometer and a polarizing beam combiner for combining optical signals emerging from the long and short arms of the imbalanced interferometer.

20 The photon state polarization converter comprises in some embodiments an optical switch device configured to selectively transmit the first time-bin of the time-bin and phase states encoded photon into the long arm of the imbalanced interferometer and the second time-bin of the time-bin and phase states encoded photon into the short arm of the imbalanced interferometer.

25 The photon state polarization converter comprises in some embodiments a first intensity modulator configured to selectively block passage of the first time-bin of the time-bin and phase states encoded photon through the short arm of the imbalanced interferometer, and a second intensity modulator configured to selectively block passage of the second time-bin of the time-bin and phase states encoded photon through the long arm of the imbalanced interferometer.

30 The photon state polarization converter can comprise a first driver unit configured to operate the first intensity modulator to periodically block passage of the first time-bin of the time-bin and phase states encoded photon through the short arm, and a second driver unit configured to operate the second intensity modulator to periodically block passage of the second time-bin of the time-bin and phase states encoded photon through the long arm. The driver units can be configured to set timing, frequency and/or bias to periodically block the respective time-bins.

The photon state polarization converter can comprise an intensity modulator configured to selectively block passage of the first and third optical pulse signals through an output of the imbalanced interferometer.

In another aspect there is provided a quantum communication system comprising
5 transmitter and receiver systems configured to communicate over a free space medium, the transmitter system comprising a quantum transmitter configured to generate time-bin and phase states modulated photons, and the photon state polarization converter of any of the embodiments disclosed herein optically coupled to the quantum transmitter for converting
10 time-bin and phase states encoded photons thereby generated into hybrid time-bin and polarization states encoded photons for transmission to the receiver system over the free space medium.

The quantum transmitter can be mounted in a secure location relatively remote to the photon state polarization converter and optically coupled thereto by one or more optical fibers. The receiver system can comprise a quantum receiver optically coupled to a photon state
15 polarization converter configured to convert hybrid time-bin and polarization states photons received over the free space medium into time-bin and phase states encoded photons. The quantum receiver is optionally mounted in a secure location relatively remote to the photon state polarization converter and optically coupled thereto by one or more optical fibers.

In yet another aspect there is provided a polarization photon states encoder comprising:
20 a coherent light source of a defined linear polarization orientation; an interferometer optically coupled to the coherent light source and configured with a polarizing beam combiner for combining optical signals emerging from arms thereof; first and second modulators configured to respectively modulate amplitude and phase of optical signals passing through the arms; and a half wavelength phase retarder configured to shift polarization orientation of optical signals
25 passing through one of the arms. The polarization photon states encoder can comprise separate amplitude and phase modulators in each of the arms. Alternatively, the polarization photon states encoder comprises a single intensity modulator in each of the arms configured to modulate both amplitude and phase of the optical signals. Optionally, the polarization photon states encoder comprises a single intensity modulator in each of the arms configured to
30 modulate both amplitude and phase of the optical signals.

In yet another aspect there is provided a quantum communication system comprising transmitter and receiver systems configured to communicate over free space medium or optical fibers, wherein the transmitter system comprising a quantum transmitter comprising the polarization photon states encoder according to any of the embodiments disclosed herein.

In yet another aspect there is provided a method of converting photon state polarization, the method comprising passing time-bin and phase states encoded photons through an imbalanced interferometer configured to generate a first optical pulse signal responsive to a first time-bin of the time-bin and phase states encoded photon emerging through a short arm of the imbalanced interferometer, a second optical pulse signal responsive to an interference pattern between the first time-bin emerging through a long arm of the imbalanced interferometer and a second time-bin of the time-bin and phase states encoded photon emerging through said short arm, and a third optical pulse signal responsive to the second time-bin emerging through the long arm of the imbalanced interferometer, and setting orthogonal polarization orientations to light components from said imbalanced interferometer and thereby generating hybrid time-bin and polarization states encoded photons.

The method can comprise setting one light components from the imbalanced interferometer into a horizontal orientation and another light component therefrom into a vertical polarization orientation. The method can comprise applying a half wavelength phase shift to one the light components from the imbalanced interferometer.

The time-bin and phase states encoded photons can have a defined linear polarization orientation, and in this case the method can comprise applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer. The time-bin and phase states encoded photons can have a defined diagonal polarization orientation, and in this case the method can comprise splitting the time-bin and phase states encoded photons into orthogonally polarized light components into the long and short arms of the imbalanced interferometer and applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer.

The time-bin and phase states encoded photons can have a defined linear polarization orientation, and the can method comprise in this case applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer and combining orthogonally polarized optical signals emerging from the long and short arms of the imbalanced interferometer.

The method can comprise selectively transmitting the first time-bin of the time-bin and phase states encoded photon into the long arm of the imbalanced interferometer and selectively transmitting the second time-bin of the time-bin and phase states encoded photon into the short arm of the imbalanced interferometer.

The method can comprise selectively blocking passage of the first time-bin of the time-bin and phase states encoded photon through the short arm of the imbalanced interferometer,

and selectively blocking passage of the second time-bin of the time-bin and phase states encoded photon through the long arm of the imbalanced interferometer.

The method of comprises in some embodiments selectively blocking passage of the first and third optical pulse signals through an output of the imbalanced interferometer. The foregoing has
5 broadly outlined features and advantages of the disclosed subject matter for better understanding of the detailed description hereinbelow. Further features and advantages of the invention will be described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to
10 the accompanying drawings. Features shown in the drawings are meant to be illustrative of only some embodiments of the invention, unless otherwise implicitly indicated. In the drawings same reference signs are used to indicate members (configural elements) having identical or corresponding functions and/or structures, and in which:

Figs. 1A to 1C schematically illustrates FSO quantum communication system according to possible embodiments;

Figs. 2A to 2C schematically illustrate FSO based receiver and transmitter configurations of possible embodiments, wherein **Fig. 2A** shows components of a possible receiver system, **Fig. 2B** shows components of a possible transmitter system, and **Fig. 2C**
20 shows a possible polarization plane aligner implementation;

Figs. 3A to 3E schematically illustrate T2H converter configurations of possible embodiments for converting time-bin and phase state encoded photons into hybrid time-bin and polarization encoded photons, wherein **Fig. 3A** demonstrates use of polarizers in a polarization stage of the converter, **Fig. 3B** demonstrates use of a half wavelength phase
25 retarder in the polarization stage of the converter, and **Figs. 3C to 3E** demonstrates use of a half wavelength phase retarder in the long arm of an imbalanced interferometer of converter implementations configured to receive polarized P-T states encoded photons;

Figs. 4A to 4C schematically illustrate T2H converter configurations of possible embodiments configured to transmit one component responsive to an interference pattern of
30 time-bins of linearly polarized P-T states encoded photons, wherein the converter of **Fig. 4A** utilizes optical switching at the input of the imbalanced interferometer, the converter of **Fig. 4B** utilizes intensity modulators at the arms of the imbalanced interferometer, and the converter of **Fig. 4C** utilizes an intensity modulator at the output of its imbalanced interferometer;

Fig. 5 schematically illustrate a setup for generation of polarization states encoded photons according to possible embodiments;

Fig. 6 schematically illustrates a setup for processing polarization state encoded photons according to possible embodiments;

5 **Fig. 7** schematically illustrates a closed loop control scheme according to possible embodiments for phase and/or polarization drifts compensation; and

Figs. 8A and **8B** schematically illustrate point-to-multipoint passive network configuration according to possible embodiments.

DETAILED DESCRIPTION OF EMBODIMENTS

10 One or more specific and/or alternative embodiments of the present disclosure will be described below with reference to the drawings, which are to be considered in all aspects as illustrative only and not restrictive in any manner. It shall be apparent to one skilled in the art that these embodiments may be practiced without such specific details. In an effort to provide a concise description of these embodiments, not all features or details of an actual
15 implementation are described at length in the specification. Elements illustrated in the drawings are not necessarily to scale, or in correct proportional relationships, which are not critical. Emphasis instead being placed upon clearly illustrating the principles of the invention such that persons skilled in the art will be able to make and use the embodiments hereof, once they understand the principles of the subject matter disclosed herein. This invention may be
20 provided in other specific forms and embodiments without departing from the essential characteristics described herein.

Time-bin and polarization states photon encoding configuration are disclosed, suitable for quantum communication over free space medium. A specially designed T2H converter utilizing an imbalanced interferometer is used in some embodiments to convert time-bin and
25 phase states encoded photons into hybrid time-bin and polarization states encoded photons suitable for the quantum communication over the free-space medium. A combiner at the output of the imbalanced interferometer may be configured to combine optical signals from the long and short arms of the imbalanced interferometer and split the combined signals into at least two separate optical signal components/transmission arms.

30 The T2H converter can utilize a polarization stage having two polarizing and/or phase retardation elements in one or both of the optical signal transmission arms, and configured to apply polarization states to the converted photons. For example, a different polarizer can be used in each one of the optical signal transmission arms for orthogonally polarizing the optical

signal components passing through the optical signal transmission arms one with respect to the other. Alternatively, a half wavelength phase retarder can be used in one of the signal transmission arms to affect the orthogonal polarization between the optical signal components passing through the optical signal transmission arms.

5 In other implementations, the T2H converter is configured to convert time-bin and phase encoded photons received therein with a certain polarization, by utilizing a half wavelength phase retarder in one of the arms on the imbalanced interferometer *e.g.*, instead of the polarization stage. In such implementations one of the signal transmission arms from combiner of the imbalanced interferometer may be used for outputting the hybrid time-bin and
10 polarization states encoded photons, and the other signal transmission arms may be used for monitoring this photons or omitted.

In another implementation of the T2H converter configured to convert time-bin and phase encoded photons received therein with a certain polarization, a 1:2 optical switch element is used to selectively introduce the first time-bin (P_0) of the time-bin and phase states encoded
15 photons only into the long arm of the imbalanced interferometer having the half wavelength phase retarder, and to selectively introduce the second time-bin (P_τ) of the time-bin and phase states encoded photons only into the short arm of the imbalanced interferometer. This way, the combined optical signals generated by the beam combiner of the imbalanced interferometer are only responsive to interference patterns of the first and second time-bins (P_0, P_τ) of the time-bin
20 and phase states encoded photons obtained therein.

In yet another implementation of the T2H converter configured to convert time-bin and phase encoded photons received therein with a certain polarization, an intensity modulator is used in the long arm of the imbalanced interferometer having the half wavelength phase retarder, and another intensity modulator is used in the short arm of the imbalanced
25 interferometer. The intensity modulators are configured to selectively block passage of the first time-bin (P_0) of the time-bin and phase states encoded photons through the short arm of the imbalanced interferometer and to selectively block passage of the second time-bin (P_τ) of the time-bin and phase states encoded photons through the long arm of the imbalanced interferometer. This way, the combined optical signals generated by the beam combiner of the
30 imbalanced interferometer are only responsive to interference patterns of the first and second time-bins of the time-bin and phase states encoded photons obtained therein.

For an overview of several example features, process stages, and principles of the invention, the example setups illustrated schematically and diagrammatically in the figures are intended for QKD applications. These QKD systems are shown as one example implementation

that demonstrates a number of features, processes, and principles used for quantum communication suitable for FSO, but they are also useful for other applications and can be made in different variations. Therefore, this description will proceed with reference to the shown examples, but with the understanding that the invention recited in the claims below can also be implemented in myriad other ways, once the principles are understood from the descriptions, explanations, and drawings herein. All such variations, as well as any other modifications apparent to one of ordinary skill in the art and useful in quantum communication applications may be suitably employed, and are intended to fall within the scope of this disclosure.

Fig. 1A schematically illustrates a communication system **10** configured in some embodiments for quantum communication over free space medium **10q**. The communication system **10** comprises a transmitter system **12** and a receiver system **11** configured for quantum communication over a free space communication link **10q**, and for conventional data (*e.g.*, packets based) communication over a standard communication link (*e.g.*, over optical fiber(s) and/or optical and/or radiofrequency based over free space) **10s**. The transmitter **12** comprises secured sub-system **12u** comprising sensitive components, a T2H converter **12t** optically coupled to the secured sub-system **12u** over optical fiber(s) **12o**, and a free space optical (*e.g.*, using telescope and/or collimating optics) system **12e** optically coupled to the T2H converter **12t**.

In some embodiments the secured sub-system **12u** comprises a quantum communication transmitter (**qTx**) **12p**, and router and cryptography key components **12y** for carrying out cryptographic key generation and communication. The router and cryptography key components **12y** can be coupled to transceiver unit **12n** configured to carry the communication over the standard communication link (*e.g.*, over optical fiber(s) and/or optical and/or radiofrequency based over free space) **10s**. The router and cryptography key components **12y** can be configured to communicate with the quantum communication transmitter **12p** over (*e.g.*, key channel and/or service channel) a standard parallel or serial data communication bus (*e.g.*, USB, Ethernet, SCSI, or suchlike), or wirelessly (*e.g.*, WiFi, Bluetooth, Zigbee, or suchlike – assuming all sensitive components are located in a well secured facility). In possible embodiments the secured sub-system **12u** is located in a secured location which can be placed relatively remote from the insecure components of the system, such as the T2H converter, the FSO system **12e**, and/or the transceiver unit **12n**.

The receiver system **11** comprises in this non-limiting example a FSO system (*e.g.*, using telescope and/or collimating optics) **11e** in line-of-sight (LOS) with the FSO system of

the transmitter system **12**, a hybrid time-bin and polarization states to time-bin and phase states photon encoding (H2T) converter **11t**, a quantum receiver (**qRx**) and router and cryptography key generation unit **11f**, and a transceiver unit **11n** electrically coupled to the router and cryptography key generation unit **11f** and configured to carry the communication over the standard communication link **10s** with the transceiver unit **12n** of the transmitter system **12**. As seen, in this example, the secure and insecure components of the receiver system **11** are located in the same location, which may be secured and/or not suitable for the physical separation *e.g.*, if mounted on a satellite.

This configuration allows generation of T-P states encoded photons in the secured location in which the quantum transmitter **12p** is located, and securely transmitting them to the T2H converter **12t** over optical fiber(s) **12o** for conversion into the hybrid time-bin and polarization states photon encoding and transmission over the free space medium **10q** to the receiver system **11** by the FSO system **12e**.

Fig. 1B schematically illustrates a communication system **10'** similar to the communication system **10** of **Fig. 1A**, but in which the secure and insecure components of the transmitter system **12** *i.e.*, quantum transmitter (**qTx**), router and cryptography key generation unit **12f**, the FSO system **12e**, the T2H converter **12t**, and the transceiver **12n**, are located in the same secure place, which may not be suitable for the physical separation *e.g.*, if mounted on a satellite. The receiver system **11'** in this example is separated into a secured sub-system **11u** comprising the quantum receiver (**qRx**) **11p** and router and cryptography key generation unit **11y**, and an insecure sub-system comprising the a hybrid time-bin and polarization states to time-bin and phase photon encoding (H2T) converter **11t**, and the FSO system **11e**. The quantum receiver **11p** can be configured to securely communicate with the H2T converter **11t** over optical fiber(s) **11o**, and the router and cryptography key components **11y** can be configured to communicate with the quantum communication transmitter **11p** over (*e.g.*, key channel and/or service channel) a standard parallel or serial data communication bus (*e.g.*, USB, Ethernet, SCSI, or suchlike), or wirelessly (*e.g.*, WiFi, Bluetooth, Zigbee, or suchlike – assuming all sensitive components are located in a well secured facility).

This configuration allows converting by the H2T converter **11t** the hybrid time-bin and polarization states photon encoding received over the free space medium **10q** by the FSO system **11e** into T-P states encoded photons, and securely transmitting the T-P states encoded photons to the secured location in which the quantum receiver **11p** is located, over the optical fiber(s) **11o**.

Fig. 1C schematically illustrates a communication system **10''** similar to the communication systems **10** and **10'** of **Figs. 1A** and **1B** respectively, but in which the secure and insecure components of the transmitter system **12** and of the receiver system **11'** are separated, as explained hereinabove in details. Accordingly, in the communication system **10''** of **Fig. 1C**, at the transmitter **12**, T-P states encoded photons are generated in the secured location in which the quantum transmitter **12p** is located, and securely transmitted to the T2H converter **12t** over optical fiber(s) **12o** for converting them into the hybrid time-bin and polarization states photon encoding and transmission over the free space medium **10q** to the receiver system **11** by the FSO system **12e**. At the receiver, the H2T converter **11t** converts the hybrid time-bin and polarization states photon encoding received over the free space medium **10q** by the FSO system **11e** into T-P states encoded photons, and securely transmits the T-P states encoded photons over the optical fiber(s) **11o** to the secured location in which the quantum receiver **11p** is located.

The quantum transmitter (**qTx**) **12p** and/or receiver (**qRx**) **11p** of embodiments hereof can be implemented by any of the embodiments disclosed in International Patent Application Nos. PCT/IL2021/050322, PCT/IL2021/050822, PCT/IL2022/051129, PCT/IL2023/050018, of the same Applicant hereof, the disclosures of which are incorporated herein by reference.

T2H converters of embodiments hereof rely on basic properties of T-P state photon encoding schemes, as exemplified hereinbelow. T-P state photon encoding is typically based on transmission of 4 (four) orthogonal phase and/or amplitude/intensity states, each composed of two consecutive phase/intensity encoded optical signal pulses, designated as: $|0\rangle$, $|1\rangle$, $|p\rangle$, $|m\rangle$. **Table 1** summarizes the intensity (normalized to 1) and phase on each time-bin/pulse of a T-P state encoded photon according to possible embodiments.

It should be noted that it is also possible to transmit different intensity levels for decoy-state implementation in the same manner.

Table 1 - transmitted states with time-bin and phase (T-P) photon coding

	P_0	P_τ
$ 0\rangle$	$P = 1, \varphi = 0$	$P = 0$
$ 1\rangle$	$P = 0$	$P = 1, \varphi = 0$
$ p\rangle = \frac{ 0\rangle + 1\rangle}{\sqrt{2}}$	$P = 1/2, \varphi = 0$	$P = 1/2, \varphi = 0$
$ m\rangle = \frac{ 0\rangle - 1\rangle}{\sqrt{2}}$	$P = 1/2, \varphi = 0$	$P = 1/2, \varphi = \pi$

wherein τ is the time difference between the P_0 and P_τ time-bins of the T-P photon encoding.

The measurement apparatus receiving these T-P state encoded photon typically utilizes an un-balanced interferometer to differentiate between the $|p\rangle, |m\rangle$ superposition states, and two or more detectors with a high enough timing resolution to differentiate between the different time-bins/pulses. The optical signal outputted from the un-balanced interferometer for each T-P state encoded photon is characterized by at least the following 3 (three) distinguishable optical pulse signals:

1. St_0 : responsive to the first optical time-bin pulse signal P_0 of the T-P state encoded photon emerging through the short arm of the imbalanced interferometer.
2. St_1 : responsive to the first optical time-bin pulse signal P_0 of the T-P state encoded photon emerging through the long arm of the imbalanced interferometer, and the second optical time-bin pulse signal P_τ of the T-P state encoded photon emerging through the short arm of the imbalanced interferometer, which in some embodiments are caused to interfere with each other.
3. St_2 : responsive to the second optical time-bin pulse signal P_τ of the T-P state encoded photon emerging through the long arm of the imbalanced interferometer.

The time difference (*e.g.*, as received at the receiver system) between the St_0 , St_1 and St_2 , optical pulse signals is thus also τ .

Accordingly, when the $|0\rangle$ or $|1\rangle$ T-P photon encoded state is optically processed at the receiver, the optical signals outputted by the imbalanced interferometer (*e.g.*, **62** in **Fig. 6**) are simply the result of splitting and combining the optical signals (or probabilities) from both the short and long arms of the imbalanced interferometer. When the $|p\rangle$ or $|m\rangle$ T-P photon encoded state is optically processed at the receiver, the optical signals St_1 outputted by the imbalanced interferometer is responsive to interference patterns occurring due to the interference between the optical signals P_0, P_τ emerging through the long and short arms of the imbalanced interferometer. At the receiver system, for each of the $|p\rangle$ and $|m\rangle$ T-P photon encoded states, one output arm split from the receiver's imbalanced interferometer (*e.g.*, interferometer **62** in **Fig. 6** having the output arms **63**) will receive optical signals which are responsive to constructive interference of the $|p\rangle$ and $|m\rangle$ T-P photon encoded states, and the other output arm will receive optical signals which are responsive to destructive interference of the $|p\rangle$ and $|m\rangle$ T-P photon encoded states, both centered about the St_1 optical pulse signal.

Table 2 summarizes the normalized probability of a photon to exit the unbalanced interferometer from each arm at a certain time-bin t_0 , t_1 and t_2 , wherein **Arm0** is the short arm and **Arm1** is the long arm of the imbalanced interferometer.

Table 2 – photon probability for each interferometer output arm (63) per each input state

	Arm_0, t_0	Arm_0, t_1	Arm_0, t_2	Arm_1, t_0	Arm_1, t_1	Arm_1, t_2
$ 0\rangle$	1/4	1/4	0	1/4	1/4	0
$ 1\rangle$	0	1/4	1/4	0	1/4	1/4
$ p\rangle = \frac{ 0\rangle + 1\rangle}{\sqrt{2}}$	1/8	1/2	1/8	1/8	0	1/8
$ m\rangle = \frac{ 0\rangle - 1\rangle}{\sqrt{2}}$	1/8	0	1/8	1/8	1/2	1/8

For example, these photon detection probabilities can be verified if each arm of the imbalanced interferometer (62) is terminated with a single photon (*e.g.*, Geiger-mode avalanche photodiode or a superconducting nanowire detector) detector configured to measure the optical signals emerging therethrough. Accordingly, based on the basis (the $|0\rangle$, $|1\rangle$ basis or the $|p\rangle$, $|m\rangle$ basis) used for the T-P photon state encoding, the measuring single photon detector (*e.g.*, 21a and 21b in Fig. 2A) used, and the measurement time-bin (t_0 , t_1 or t_2), it is possible to identify the transmitted T-P photon encoding state. For each measurement result, there is a probability to get an inconclusive result (marked by a question mark “?” in Table 3), as required by the QKD protocol.

Table 3 - Interpretation of the measurement result (the question mark means that it is not possible to know the state for that measurement result.)

	$ 0\rangle, 1\rangle$ basis	$ p\rangle, m\rangle$ basis
Det0 t_0	$ 0\rangle$	?
Det0 t_1	?	$ p\rangle$
Det0 t_2	$ 1\rangle$	?
Det1 t_0	$ 0\rangle$	?
Det1 t_1	?	$ m\rangle$
Det1 t_2	$ 1\rangle$	?

In embodiments hereof the T2H converter 12t is configured to produce the four encoded photonic states presented in Table 3, which are derived from three distinguishable time-bin and polarization encoded optical signal pulses (also referred to herein as hybrid photon encoding states) St_0 , St_1 , St_2 , for each T-P encoded photon $\langle P_0, P_\tau \rangle$ thereby received. The P_0 is the first transmitted optical time-bin pulse signal of the T-P encoded photon, and P_τ is the second transmitted optical time-bin pulse signal of the T-P encoded photon.

A first possible hybrid T-P and polarization photon state encoding scheme/basis is described hereinbelow. This hybrid encoding scheme/basis can be easily generated by

polarization of the optical signals emerging from the imbalanced interferometer, it is simple to measure, and robust to atmospheric effects. **Table 4** presents the transmitted photon encoding states/basis of such possible hybrid time-bin and polarization photon state encoding in possible embodiments.

- 5 For the use with polarization maintaining (PM)-fibers, one can define the fast axis as H (*i.e.*, horizontal polarization $|H\rangle$), and the slow axis as V (*i.e.*, vertical polarization $|V\rangle$), for example. The signs between the $|H\rangle \pm |V\rangle$ superposition states can differ in different embodiments, and can also randomly change over time between the different linear, circular and elliptical polarizations.
- 10 **Table 4** – hybrid time-bin and polarization photon encoding states of possible embodiments *i.e.*, using time-bin and polarization coding (the intensities P are normalized to a certain number, chosen as “1” here for simplicity)

	$t = 0$	$t = \tau$	$t = 2\tau$
$ 0\rangle$	$P = 1/2, H\rangle \pm V\rangle$	$P = 1/2, H\rangle \pm V\rangle$	0
$ 1\rangle$	0	$P = 1/2, H\rangle \pm V\rangle$	$P = 1/2, H\rangle \pm V\rangle$
$ p\rangle$	$P = 1/4, H\rangle \pm V\rangle$	$P = 1/2, H\rangle$	$P = 1/4, H\rangle \pm V\rangle$
$ m\rangle$	$P = 1/4, H\rangle \pm V\rangle$	$P = 1/2, V\rangle$	$P = 1/4, H\rangle \pm V\rangle$

- The measurement is performed in some embodiments at the QKD receiver after passing the transmitted signal through a polarizing beam splitter, PBS **21** in **Fig. 2A**, configured to split the optical signals thereby received into two or more light component arms. One light component arm from the PBS **21** can be configured for passage of only the horizontally ($|H\rangle$) polarized light components received in the PBS **21** (*e.g.*, to detector **21a**), and another light component arm thereof can be configured for passage of only the vertically ($|V\rangle$) polarized light components received in the PBS **21** (*e.g.*, to detector **21a**). Accordingly, the receiver **11/11'** illustrated in **Fig. 2A** is configured to process and extract the information encoded in the hybrid time-bin and polarization states encoded photons without an interferometer. **Table 5** summarizes the probabilities for photons to pass through each of the light component arms of the PBS (**Arm_H** and **Arm_V**) at the receiver.
- 25 **Table 5** - the optical signal probability/power getting to each of the PBS's output light component arms at the receiver side

	Arm_H, t_0	Arm_H, t_1	Arm_H, t_2	Arm_V, t_0	Arm_V, t_1	Arm_V, t_2
$ 0\rangle$	1/4	1/4	0	1/4	1/4	0
$ 1\rangle$	0	1/4	1/4	0	1/4	1/4
$ p\rangle$	1/8	1/2	1/8	1/8	0	1/8
$ m\rangle$	1/8	0	1/8	1/8	1/2	1/8

In possible embodiments each of the PBS's light component arms at the receiver is terminated with a single photon detector - Det0 for $\mathbf{Arm}_H$ and Det1 for $\mathbf{Arm}_V$. The interpretation of the states is the same as shown in **Table 3**.

- 5 A second hybrid time-bin and polarization photon encoding scheme/basis according to other possible embodiments hereof is disclosed hereinbelow. This hybrid photon state encoding scheme utilizes superpositions of the $|H\rangle$ and $|V\rangle$ linear polarizations, as presented in **Table 6**. **Table 6** - transmitted hybrid photon encoding states with time-bin and polarization coding (2nd option, wherein the intensities P are normalized to 1).

	$t = 0$	$t = \tau$	$t = 2\tau$
$ 0\rangle$	$P = 1/2, H\rangle$	$P = 1/2, - V\rangle$	0
$ 1\rangle$	0	$P = 1/2, H\rangle$	$P = 1/2, - V\rangle$
$ p\rangle$	$P = 1/4, H\rangle$	$P = 1/2, H\rangle - V\rangle$	$P = 1/4, - V\rangle$
$ m\rangle$	$P = 1/4, H\rangle$	$P = 1/2, H\rangle + V\rangle$	$P = 1/4, - V\rangle$

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With reference to **Fig. 2A**, the measurements are performed at the receiver **11/11'** in some embodiments after passing the optical signal through a PBS **21** having at least two light component arms (of detectors **21a, 21b**) into which the split optical signals from the PBS **21** are directed.

- 15 If the PBS **21** is aligned at 45° relative to the transmission setup **12/12'** (or using half wavelength phase retarder **10r** waveplate before the PBS), one light component arm of the receiver's PBS passes only the transmitted $|H\rangle + |V\rangle$ polarization light component, and its other light component arm passes only the transmitted $|H\rangle - |V\rangle$ polarization light component. It is noted that half wavelength phase ($\lambda/2$) retarder **10r** may be used either in the receiver system
- 20 **11/11'**, anterior or posterior to its FSO system **11e**, in the transmitter system **12/12'**, or anywhere in between them, to align the PBS **21** and the transmission setup one with respect to the other. **Table 7** summarizes the probabilities for photons to pass through the receiver's PBS **21** to each of its light component arm ($\mathbf{Arm}_{0+}$ and $\mathbf{Arm}_{1-}$) *i.e.*, when each of the light component arms from the receiver's PBS **21** is terminated with a single photon detector,
- 25 Detector-a **21a** for $\mathbf{Arm}_{0+}$ and Detector-b **21b** for $\mathbf{Arm}_{1-}$. The interpretation of the measurement results/states is the same as shown in **Table 3**.

Table 7 - the optical signal probability/power at each output light component arm from the receiver's PBS

	$\mathbf{Arm}_{0+}, t_0$	$\mathbf{Arm}_{0+}, t_1$	$\mathbf{Arm}_{0+}, t_2$	$\mathbf{Arm}_{1-}, t_0$	$\mathbf{Arm}_{1-}, t_1$	$\mathbf{Arm}_{1-}, t_2$
$ 0\rangle$	1/4	1/4	0	1/4	1/4	0

$ 1\rangle$	0	1/4	1/4	0	1/4	1/4
$ p\rangle$	1/8	0	1/8	1/8	1/2	1/8
$ m\rangle$	1/8	1/2	1/8	1/8	0	1/8

If the measurement basis used at the receiver (*e.g.*, randomly) changes for every time-bin, (*e.g.*, by measuring S_{t0} in the H/V basis, S_{t1} in the diagonal p/m basis, and S_{t2} in the H/V basis) better SNR can be achieved. The photons/optical signals arriving at the receiver during the time intervals are:

$t = 0$ are always in the $|H\rangle$ polarization;

$t = \tau$ are always in the $|H\rangle + |V\rangle$ or the $|H\rangle - |V\rangle$ polarization; and

$t = 2\tau$ are always in the $|V\rangle$ polarization.

Therefore, measuring the optical signals at the receiver with the right measurement basis means that only one detector measures meaningful data for each of the $t=0$ (t_0), $t=\tau$ (t_1) and $t=2\tau$ (t_2) time intervals, as seen in **Table 8**.

Table 8 - the optical signal probability/power for each light component arm detector of the receiver's PBS

	Arm_{0+}, t_0	Arm_{0+}, t_1	Arm_{0+}, t_2	Arm_{1-}, t_0	Arm_{1-}, t_1	Arm_{1-}, t_2
$ 0\rangle$	1/2	1/4	0	0	1/4	0
$ 1\rangle$	0	1/4	0	0	1/4	1/2
$ p\rangle$	1/4	0	0	0	1/2	1/4
$ m\rangle$	1/4	1/2	0	0	0	1/4

The interpretation of the measurement results is presented in **Table 9**. As seen, there are fewer possible results since the signal is always collected in the right measurement basis, which improves the SNR of the $|0\rangle$ and $|1\rangle$ photon encoding states, compared to the previous measurement scheme.

Table 9 - measurement result interpretation for the states presented in **Table 8** (the question mark means that it is not possible to know the state for that measurement result.)

	$ 0\rangle, 1\rangle$ basis	$ p\rangle, m\rangle$ basis
Det0 t_0	$ 0\rangle$	?
Det0 t_1	?	$ p\rangle$
Det1 t_1	?	$ m\rangle$
Det1 t_2	$ 1\rangle$	?

A yet another (3rd option) hybrid time-bin and polarization photon encoding scheme/basis of embodiments hereof is based on measuring at the receiver only the optical signals received in the $t=\tau$ (t_1) time-bin *e.g.*, to perform the polarization based BB84. In this case the time-bins $t=0$ (t_0) and $t=2\tau$ (t_2) can be used for polarization plane alignment, as illustrated in **Fig. 7**, as the signals measured during the $t=0$ (t_0) time-bin is always of one specific polarization direction and $t=2\tau$ (t_2) is always the orthogonal polarization direction.

Yet another hybrid time-bin and polarization scheme/basis (4th option) of embodiments hereof utilizes the $|p\rangle$, $|m\rangle$, $|r\rangle$, $|l\rangle$ bases, which keeps the information of the $t=0$ (t_0) and $t=2\tau$ (t_2) identical between all states, and encodes the information only in $t=\tau$ (t_1) time interval. This configuration increases the level of security compared to embodiments that include the $|0\rangle$, $|1\rangle$ states, that as shown in **Table 6** for example, may not have any optical power at the $t=0$ and $t=2\tau$ time intervals. When using only the $|p\rangle$, $|m\rangle$, $|r\rangle$, $|l\rangle$ states, using active methods to prevent data transmission in the $t=0$ and $t=2\tau$ time intervals (*i.e.*, by generating pure polarization states, as exemplified in **Figs. 4A, 4B** and **5**) is not required.

Few techniques of generating the hybrid time-bin and polarization photon encoding according to embodiments hereof are described hereinbelow. As demonstrated in **Fig. 2B**, in possible embodiments a T-P encoder **12c** of the quantum transmitter **12p** generates the P_0, P_τ time-bin and phase encoded quantum states *e.g.*, according to **Table 1** hereinabove. The generated P_0, P_τ time-bin and phase quantum state encoded photons are then converted by the T2H unit **12d** (*e.g.*, using any of the T2H converters disclosed herein) into hybrid time-bin and polarization state encoded photons St_0, St_1, St_2 . The output of the T2H converter **12d** can be then passed through a polarization plane aligner **20**, and thereafter transmitted over the free space medium **10q** by the FSO system **12e**. It is however noted that the polarization plane aligner **20** can be located either at the transmitter system **12/12'**, at the receiver system **11/11'**, or anywhere between the transmitter and receiver systems.

The polarization plane aligner **20** is configured to compensate for rotations along the Bloch-sphere in the polarization plane between the output of the transmitter **12/12'** system and the PBS **21** of the receiver system **11/11'**. Such rotations can be the result of the relative rotation between the output optical fiber of the transmitter system **12/12'** and the polarizer *e.g.*, PBS **21** of the receiver system **11/11'**, for example. The polarization plane aligner **20** is configured in some embodiments to align the hybrid time-bin and polarization states encoded photons generated by the T2H unit **12d**, such that at the optical signals from the transmitter system

12/12' *e.g.*, the transmitted H (V) polarization, is aligned with the polarization of the receiver system **11/11'** *e.g.*, the H (V) polarization of the receiver's PBS **21**.

The polarization plane aligner **20** is exemplified in **Fig. 2B** in the transmitter system **12'**, but it can be similarly installed in the receiver system **11/11'** *e.g.*, after the FSO system **11e**, or anywhere between the transmitter **12/12'** and receiver **11/11'** systems. After the polarization alignment is performed *e.g.*, at the receiver system **11/11'**, the states of the hybrid time-bin and polarization state encoded photons are analyzed and measured by the receiver's PBS **21** and the single-photon detectors **21a, 21b** coupled to its light component arms.

Fig. 2C demonstrates a polarization plane aligner **20** according to possible embodiments. The polarization plane aligner **20** is generally configured to convert between linear, circular, and elliptical polarization states. It is used in possible embodiments to compensate for polarization scrambling that occurs in optical fibers, or while passing through other physical mediums, and to align the plane of reference in case of free space optical links, such as a satellite rotating in space relative to a ground station.

A free space implementation of the polarization plane aligner **20** can utilize a cascade combination of half ($\lambda/2$) and quarter ($\lambda/4$) phase retarder wave-plates **r1, r2, r3, ...**. A fiber-based implementation can use stress-induced birefringence Polarization Controllers, such as the motorized fiber polarization controller MPC320 manufactured by Thorlabs. Such polarization aligning instruments are usually opto-mechanical devices that are tuneable by electrical control signals. For a general case, such a polarization plane alignment instrument **20** generally requires a simultaneous closed-loop control of 3 DOF, as demonstrated in **Fig. 2C**. In this non-limiting example, the polarization plane alignment **20** comprises a sequence of a $\lambda/4$ phase retarder (**r1**), a $\lambda/2$ phase retarder (**r2**), and $\lambda/4$ phase retarder (**r3**), each coupled to a respective rotation angle control actuator **Act1, Act2** and **Ac3**, and optional gear system **g1, g2** and **g3**.

In possible embodiments optical coupling **22** is used for monitoring the polarization of the optical signals inputting and/or outputting the polarization plane alignment **20** by a detector **27**. A control unit **28** can be used to process the measurement signals from the detector **27** and generate based thereon control signals for activating at least one of the actuators **Act1, Act2** and/or **Ac3**, in order to convert the polarization orientation of the optical signal between the linear, circular, and elliptical polarization states.

The purpose of generating polarization encoded photons in some embodiments is to perform QKD over a free-space medium (not over optical fiber). It is thus assumed that the state of polarization is maintained from the output of the transmitter (**12/12'**) to the input of the

receiver (**11/11'**). The optical coupling **22** of the photons in and out of the optical fiber **20f** can be carried out by collimators, lenses, telescopes etc. While progressing through a single-mode optical fiber, the level of polarization slowly degrades. While progressing through a polarization maintaining fiber (PM) the $|H\rangle$ and $|V\rangle$ polarizations are maintained, but the phase
 5 between them, which determines the superposition states is not maintained. Passing through unbalanced interferometers with a PBS input, whether in the transmitter (**12/12'**) or the receiver (**11/11'**), also adds a phase between the $|H\rangle$ and $|V\rangle$ polarization orientations.

The optics of the transmitter and receiver can be designed to have a well defined plane of reference with a well-defined $|H\rangle$ and $|V\rangle$ polarization orientations. To align the $|H\rangle$ and $|V\rangle$
 10 polarization orientations plane two options are suggested:

- a rotation of the output (or input) PM fiber **20f**;
- a rotation of all of the transmitter or receiver optical modules; and/or
- rotation of a $\lambda/2$ phase retarder waveplate before or in the receiver (or transmitter) system (free-space or fiber based).

15 The alignment can be done independently of the correction of the phase between the $|H\rangle$ and $|V\rangle$ polarization orientations (traditionally done with a $\lambda/4$ phase retarder waveplate), with a closed loop based on optical signals with a known $|H\rangle$ and $|V\rangle$ polarization orientations, or an open loop with a define angle relative to the earth gravity or other known space orientation measurement methods.

20 The relative phase between the $|H\rangle$ and $|V\rangle$ polarization orientations is accumulated in the optical fibers and interferometers used in the system, and eventually sums to a total phase ϕ_{total} that can be generally expressed as follows:

$$\phi_{TxConverter} + \phi_{TxFiber} + \phi_{medium} + \phi_{RxInterferometer} + \phi_{RxConverter} + \phi_{RxFiber} = \phi_{total}$$

As the goal is to differentiate between the superposition stated, whether the phase is
 25 measured as diagonal polarizations or different phase states, the only phase that needs to be corrected for is the total phase *i.e.*, by setting $\phi_{total}=0$. In embodiments hereof the total phase ϕ_{total} is set to 0 (zero) by changing the transmission wavelength. Changing the wavelength results in changing the phase accumulated in each of the system segments, and especially in the interferometers where each polarization accumulates the phase differently.

30 As illustrated in **Fig. 7**, closed control-loop based on the measured values at the end of the fiber is used in some embodiments to change/adjust the wavelength (with a dithering algorithm for example) to compensate in real time for all of the phases accumulated in the system and distinguish between the different superposition states with a high resolution

(visibility > 99% for example). **Fig. 3A** shows a T2H converter **30** according to possible embodiments. The T2H converter **30** comprises an imbalanced interferometer **23r** having a long arm **Arm_l** and a short arm **Arm_s**, a polarization stage **24p** having two polarization arms **Arm_h**, **Arm_v** optically coupled to the imbalanced interferometer **23r**, a signal output arm **25t** coupled to the polarization stage **24p**, and an optional signal monitoring arm **25m** coupled to the polarization stage **24p**. The imbalanced interferometer **23r** comprises a beam splitter (BS *e.g.*, having a 50:50 splitting ratio) **23** configured to receive the T-P state encoded photons from the T-P unit **12c** over the optical fiber **12o** and split the same into the optical fibers of its long and short arms **Arm_l**, **Arm_s**.

A non-polarizing beam combiner **24** can be used to combine the optical signals emerging from the long and short arms **Arm_l**, **Arm_s** of the imbalanced interferometer **23r**. The non-polarizing beam combiner **24** can be further configured to split (*e.g.*, 50:50 splitting ratio) the combined optical signals of the long and short arms **Arm_l**, **Arm_s** into optical fibers of the polarization arms **Arm_h**, **Arm_v** of the polarization stage **24p**. Similarly, a non-polarizing beam splitter **25** can be used to combine the optical signals emerging from the polarization arms **Arm_h**, **Arm_v** of the polarization stage **24p**, and to split (*e.g.*, 50:50 splitting ratio) the combined optical signals of the polarization arms **Arm_h**, **Arm_v** into optical fibers of the output arm **25t** and of the optional signal monitoring arm **25m**. It is noted that in embodiments hereof the non-polarizing beam splitter **25** requires PM connectivity.

In this specific and non-limiting example the T-P input **12c** of the T2H converter **30** is a non-polarized time-bin and phase encoded states photons. These T-P photons pass through an unbalanced interferometer **23r** over the **non-PM** optical fibers. It is noted that though a Mach Zehnder interferometer is exemplified in the T2H converter (**12t**) implementations **30** (and **31** to **36** of **Figs. 3B-3E** and **4A-4B**) disclosed herein, the imbalanced interferometer **23r** can be similarly implemented as a Michelson interferometer with Faraday mirrors, for example. In embodiments hereof the imbalanced interferometer **23r** is configured such that the lag/time-difference between its long and short arms **Arm_l**, **Arm_s** is τ , such that the two optical time-bin signal pulses **P₀**, **P _{τ}** of the T-P photons can timely interfere with each other at the non-polarizing combiner **24** after passage through the arms **Arm_l**, **Arm_s** of the unbalanced interferometer **23r**.

The phase shift of the imbalanced interferometer **23r** and the (*e.g.*, laser) wavelength of the optical signal time-bin pulses **P₀**, **P _{τ}** thereby received, can be set such that the output optical signals of the imbalanced interferometer **23r** emerging from the beam combiner **24** is substantially as presented hereinabove in **Table 2**. The output optical signals on each light component polarization arm **Arm_h**, **Arm_v** coupled to the non-polarizing beam combiner **24** then

passes through the respective H-polarizer **24h** and V-polarizer **24v**, and therefrom into a PM optical fiber(s). After passing through the polarizers **24h,24v** the states of the optical signals in the polarization arms **Arm_h** and **Arm_v** are substantially as presented in **Table 10**:

Table 10 - the optical signal states in the polarization arms of the polarization stage **24p** after passage through the H and V polarizers **24h,24v**

	Arm_H, t_0	Arm_H, t_1	Arm_H, t_2	Arm_V, t_0	Arm_V, t_1	Arm_V, t_2
$ 0\rangle$	1/4	1/4	0	1/4	1/4	0
$ 1\rangle$	0	1/4	1/4	0	1/4	1/4
$ p\rangle$	1/8	1/2	1/8	1/8	0	1/8
$ m\rangle$	1/8	0	1/8	1/8	1/2	1/8

The polarization arms **Arm_h,Arm_v** are configured to exhibit the same time delay (*e.g.*, with lengths difference configured in accordance with the different propagation velocity of each PM fiber axis). The polarization arms **Arm_h,Arm_v** are configured to combine the optical signals propagating therethrough in the beam combiner **25** with no interference, since the polarizations of the hybrid states encoded photons of the polarizing arms **Arm_h,Arm_v** are orthogonal. The polarization of the output optical signals **25t** in some of the times and/or states is a superposition of both H and V polarized optical signals emerging through the polarizing arms **Arm_h,Arm_v**. However, since the phase shift of the combiner **25** is not necessarily stabilized, the state of the combined optical signals from the combiner **25** may change over time between the different linear, circular and elliptical polarization orientations.

As seen, the output optical signals from the arms of the combiner **25** can be used for monitoring the hybrid states encoded photons produced by the T2H converter **30** (or dumped), and for outputting the transmitted optical signal states, which can be transmitted to the receiver (*e.g.*, over FSO) *e.g.*, after passing through the polarization plane aligner **20**. The timing and polarization of the different transmitted optical signal states are substantially as presented in **Table 4** hereinabove.

Fig. 3B illustrates a possible T2H converter **31** implementation structured similar to the T2H converter **30** of **Fig. 3A**, but utilizing one or more phase retarders **24w** in the PM arms **Arm_h',Arm_v'** of the polarization stage **24p'**, instead of the H and/or V polarizers (**24h,24v**). In the T2H converter **31** exemplified in **Fig. 3B** the T-P input optical signals **12c'** are polarized time-bin and phase encoded photons. Accordingly, the optical fibers and combiner/splitter (**23',24',25'**) of the T2H converter **31** employ PM optical elements. Optionally, but in some embodiments preferably, the polarization orientation of the input signal **12c'** is linear and

aligned with either the slow or fast axis of the PM fiber. The linearly polarized photons **12c'** are passed through the PM imbalanced interferometer (*e.g.*, Mach Zehnder or a Michelson interferometer with Faraday mirrors for example) **23r'**.

The lag/time-difference between the long and short arms **Arm_l'**, **Arm_s'** of the imbalanced PM interferometer **23r'** is similarly set to τ seconds, such that the two optical signal time-bin pulses **P₀'**, **P _{τ} '** of the T-P and polarized states encoded photons can overlap after passage through the arms **Arm_l'**, **Arm_s'** and interfere with each other at the PM beam combiner **24'**. The phase shift of the imbalanced PM interferometer **23r'** and the (*e.g.*, laser) wavelength of the optical signals time-bin pulses **P₀'**, **P _{τ} '** thereby received, can be set such that the output optical signals of the imbalanced PM interferometer **23r'** emerging from the PM beam combiner **24'** is substantially as presented hereinabove in **Table 2**. The optical signals emerging through the arms **Arm_l'**, **Arm_s'** from the PM beam combiner **24'** are polarized in the same orientation *e.g.*, along the fast axis (denoted as H hereinabove).

In this non-limiting example the optical signals passing through at least one of the arms (*e.g.*, **Arm_h'**) of the polarization stage **24p'** are passed through a half-wavelength waveplate phase retarder ($\lambda/2$) **24w**. This can be implemented in a few ways, as elaborated further hereinafter. After applying the polarization rotation *e.g.*, to the slow axis (or V polarization), to the optical signals passing in at least one of the PM arms **Arm_h'**, **Arm_v'**, the states of the optical signals reaching the PM beam combiner **25'** are substantially as presented in **Table 5**.

The optical signals propagating along the PM arms **Arm_h'**, **Arm_v'**, which are configured to exhibit the same delay time (*e.g.*, with length difference taking into account the different propagation velocities of each PM fiber axis), are combined by the PM beam combiner **25'** without interference since the polarization orientations of the optical signals emerging from the PM arms **Arm_h'**, **Arm_v'** are orthogonal one with respect to the other. The polarization of the optical signal outputted from the PM beam combiner **25'** in some of the times and/or states is a superposition of the H and V polarizations in these arms. However, since the phase shift of the PM beam combiner **25'** is not necessarily stabilized, the state of the optical signal outputted from the PM beam combiner **25'** can change over time between linear, circular and elliptical polarization orientations.

In some embodiments one output of the PM beam combiner **25'** is used for monitoring the hybrid time-bin and polarization encoded photon states produced by the T2H converter **30'** (or dumped). The other output of the PM beam combiner **25'** can be used (*e.g.*, attenuated if required to an intensity level required by the QKD protocol) to transmit the hybrid time-bin and polarization states encoded photons (*e.g.*, over free space optics) to the QKD receiver *e.g.*,

after passing through the polarization plane aligner (20). The timing and polarization of the different transmitted states of the hybrid states encoded photons are presented in Table 4 hereinabove.

In the T2H converters 30 and 31 of Figs. 3A and 3B, the polarization encoding is carried out after the passing the optical signals through the imbalanced interferometer 23r. In addition, the beam splitters/combiners (23/23', 24/24', 25/25') of the T2H converters 30, 31 and 32, preferably non-polarizing beam splitters/combiners. In the following embodiments the polarization encoding is performed within the imbalanced interferometer 23r/23r'.

Fig. 3C illustrates a possible T2H converter 32 implementation structured similar to the T2H converters 30, 31 of Figs. 3A and 3B, but utilizing instead of the polarization stage 24p/24p' one or more phase retarders 24w in the arms Arm_i, Arm_s of the imbalanced interferometer 23r. Optical components (*e.g.*, fibers, combiners, splitters,...) of the T2H converter 32 of Fig. 3C are based on non-PM optical elements. In this non-limiting example, the input optical signals from the T-P unit 12c' are polarized time-bin and phase encoded photons P₀', P₁'. Optionally, but in some embodiments preferably, the polarization orientation of the input optical signals 12c' is linear *e.g.*, H-polarized.

The polarized photons P₀', P₁' from the T-P unit 12c' pass through the unbalanced (*e.g.*, fiber-based) interferometer (*e.g.*, Mach Zehnder or Michelson interferometer) 23r. The time-difference/lag between the short and long arms Arm_s, Arm_i of the imbalanced interferometer 23r is set to τ seconds, such that the two transmitted time-bins P₀', P₁' of each transmitted photon can overlap. A half waveplate phase retarder ($\lambda/2$) 23w is incorporated in one of the arms (*e.g.*, the long arm Arm_i) of the imbalanced interferometer 23r for converting the time-bins P₀', P₁' of the transmitted photons from one polarization orientation to another/orthogonal polarization orientation *e.g.*, from H-polarization into V-polarization.

For example, if a $\lambda/2$ phase retarder is used in the long arm Arm_i and the photons P₀', P₁' from the T-P unit 12c' are horizontally polarized, then the optical signals propagating towards the combiner 24 along the long arm Arm_i will become vertically polarized after passage through the phase retarder 23w, and the optical signals propagating towards the combiner 24 along the short arm Arm_s will remain horizontally polarized. For a PM optical fiber this means moving the optical signal from the fast axis to the slow axis, or vice versa, as the axes of the PM optical fiber are in the plane of reference. For polarization compensation between the short and long arms Arm_s, Arm_i of the imbalanced interferometer 23r, as well as for the polarization conversion of the phase retarder 23w, polarization controller *e.g.*, stress-induced birefringence, can be used, with the extra fiber used for the long interferometer arm.

The phase shift of the imbalanced interferometer **23r** and/or the (*e.g.*, laser) wavelength of the input optical signal **12c'**, is set such that the output optical signals of the imbalanced interferometer **23r** (emerging from the combiner **24**) has stable polarization states, substantially as presented in **Table 6**. The combiner **24** can be configured to split (*e.g.*, with a 50:50 split ratio) the combined optical signals from the imbalanced interferometer **23r** into two of more optical output arms.

In possible embodiments one optical output arm of the imbalanced interferometer **23r** is used for monitoring **25m** the hybrid states encoded photons generated by the T2H converter **32** *e.g.*, to optimize the polarization control and wavelength control (or dumped). Another optical output arm **25t** of the imbalanced interferometer **23r** can be used to transmit hybrid states encoded photons (*e.g.*, over FSO), to the QKD receiver *e.g.*, after passing through the polarization plane aligner (**20**).

It is noted that in embodiments of the T2H converters **30**, **31** and **32**, of **Figs. 3A**, **3B** and **3C**, respectively, there may be a need to maintain a high visibility interference, even when the ambient temperature is undergoing changes. In the following T2H converter embodiments there may be a need to maintain the phase difference between long and short arms **Arms_s**, **Arms_l** of the imbalanced interferometer **23r**, in order to achieve a stable diagonal polarization.

Another possible T2H converter **33** embodiment is shown in **Fig. 3D**, which is similar in many aspects to the configuration of the T2H converter **32** shown in **Fig. 3C**. A main difference between these T2H converter embodiments is that the input and output stages of the T2H converter **33** of **Fig. 3D** are constructed from non-PM optical (*e.g.*, fibers, combiners, splitters, etc.) elements, and a imbalanced PM-based interferometer stage **23r'**.

In this non-limiting example the input optical signals **12c'** are polarized time-bin and phase encoded photons **P₀'**, **P_τ'**. In addition the input of the imbalanced PM-based interferometer **23r'** is a polarizing beam splitter (PBS) **23''**, such that the one polarization (*e.g.*, H-polarization) component of the photons **P₀'**, **P_τ'** propagates into one optical arm (*e.g.*, the long arm **Arms_l**), and the orthogonal polarization (*e.g.*, V-polarization) component thereof propagates into the other arm (*e.g.*, the short arm **Arms_s**), of the imbalanced PB-based interferometer **23r'**. It is noted that in such configuration of the T2H converter there is no need for polarization control.

Optionally, but in some embodiments preferably, the input optical signals **12c'** are diagonally (+/-) polarized *e.g.*, H+V polarized. Accordingly, the polarized time-bin and phase encoded photons **P₀'**, **P_τ'** from the T-P device **12c'** are split into two optical signal components having perpendicular polarization orientations, which pass through the respective arms

Arm_s, Arm_l of the unbalanced (*e.g.*, fiber-based) PM-based interferometer (*e.g.*, Mach Zehnder or Michelson interferometer) **23r'**. The time-difference/lag between the interferometer arms is τ , such that the two transmitted time-bins **P₀, P_r'** can overlap at the combiner **24**.

The phase-difference of the interferometer and/or the (*e.g.*, laser) wavelength of the input optical signal **12c'**, can be set such that the output optical signals emerging from the combiner **24** of the imbalanced PM-based interferometer **23r'** has stable polarization states, substantially as presented in **Table 6**, that propagates into the output stage (*e.g.*, made of non-PM single mode fibers). The hybrid state encoded output photons **25t** emerging from the combiner **24** of the imbalanced PM-based interferometer **23r'** can be transmitted (*e.g.*, over FSO) to the QKD receiver *e.g.*, after passing through the polarization plane aligner (**20**). Optionally, but in some embodiments preferably, the output photons emerging from the combiner **24** are split for monitoring **25m** *e.g.*, in order to optimize the polarization control and wavelength control (or dumped).

Another possible embodiment is shown in **Fig. 3E**, which is similar in many aspects to the configuration of the T2H converter **32** shown in **Fig. 3C**. A main difference between these T2H converter embodiments is that the output stages of the T2H converter **34** of **Fig. 3E** is constructed from non-PM optical (*e.g.*, fibers, combiners, splitters, etc.) elements, while its input (**12c', 12o**) and interferometric stages (**23r**) are PM-based (*i.e.*, utilizing PM-based optical elements) imbalanced PM-based interferometer stages **23r'**. In addition, the beam splitter at the input of the imbalanced PM-based interferometer **23r'** is a non-polarizing (*e.g.*, 50:50 ratio) splitter, configured such that the input optical signals **12c'** of the T2H converter **34** propagates into both the short and the arms of the imbalanced PM-based interferometer **23r'** regardless of its polarization (*e.g.*, H-polarization).

A least one the arms **Arm_l, Arm_s** of the imbalanced PM-based interferometer **23r'** (*e.g.*, the long arm **Arm_l**) comprises a phase retarder (*e.g.*, half waveplate) element **23w** inline, to convert the polarization (*e.g.*, H polarization) of the optical signals propagating therethrough into the orthogonal polarization direction (*e.g.*, V-polarization). In the T2H converter **34** there is no need for polarization control, as it utilizes PM-based optical elements/fibers.

The input optical signals **12c'** of the T2H converter **34** is polarized time-bin and phase encoded photons **P₀, P_r'**. Optionally, but in some embodiments preferably, the input optical signals **12c'** are linearly polarized (*e.g.*, H-polarization). These polarized photons **P₀, P_r'** pass through an the unbalanced (*e.g.*, fiber-based) PM-based interferometer (*e.g.*, Mach Zehnder or Michelson interferometer) **23r'**. The time-difference/lag between the short and long arms **Arm_l, Arm_s** of the imbalanced PM-based interferometer **23r'** is set to τ seconds, such that the

two transmitted time-bins P_0', P_1' can overlap at the polarization beam combiner $24''$ at the output of the imbalanced PM-based interferometer $23r'$.

The phase-difference of the imbalanced PM-based interferometer $23r'$ and/or the (*e.g.*, laser) wavelength of the input optical signals $12c'$, are configured such that the output optical signals of the imbalanced PM-based interferometer $23r'$ has a stable polarization state, substantially as presented in **Table 6**, that propagates into the output stage (*e.g.*, made of non-PM single mode fibers). The hybrid state encoded output photons $25t$ emerging from the polarization beam combiner $24''$ of the imbalanced PM-based interferometer $23r'$ can be transmitted (*e.g.*, over FSO) to the QKD receiver. The output optical signals emerging from the polarization beam combiner $24''$ can be split for monitoring *e.g.*, to optimize the polarization control and wavelength control (or dumped).

Figs. 4A and 4B schematically demonstrate T2H converter embodiments **35,36** configured to generate pure polarization encoding states from the time-bin and phase encoded T-P photon encoding states. In these non-limiting examples active optical components are used in the T2H converters **35,36** to generate the pure polarization encoding states. The advantage of these embodiments is that the encoded optical signals (*e.g.*, in the QKD transmitter/Alice system) can be transmitted over long distances (*e.g.*, tens of kilometers) of optical fiber and only then converted to the pure polarization coding.

The T2H converter embodiments **35,36** are similar in many aspects to the configuration of the T2H converter **34** shown in **Fig. 3E**, but utilizes in possible embodiments an intensity modulator (IM) having one input and at least two outputs, or any other fast 1:2 optical switch **23s**, to selectively direct the input T-P encoded input photons $12c'$ into one of the arms **Arm_l**, **Arm_s** of the imbalanced PM-based interferometer $23r^*$. In these embodiments the optical switch (or intensity modulator) **23s** replaces the passive splitter ($23'$) at the input of the unbalanced PM-based interferometer $23r'$ of the T2H converter **34** shown in **Fig. 3E**.

With reference to **Fig. 4A**, in possible embodiments pure polarization states can be generated by switching the P_0' pulse of the T-P encoded photons $12c'$ only to the long arm **Arm_l** of the unbalanced PM-based interferometer $23r^*$, and directing the P_1' pulse of the T-P encoded photons $12c'$ only to the short arm **Arm_s** of the imbalanced PM-based interferometer $23r^*$. This way, the first and third optical pulse signals (St_0 and St_2) of the hybrid encoded photons are eliminated, and only the middle optical pulse signal (St_1) of the hybrid encoded photons are transmitted from the imbalanced PM-based interferometer $23r^*$.

Referring now to **Fig. 4B**, in some embodiments, instead of using a 1:2 optical switch or intensity modulator (**23s**), which is a unique component, at least one intensity modulator

IM1,IM2 is used in each one of the arms **Arm_s,Arm_l** of the unbalanced PM-based interferometer **23r'**. For example, at least one intensity modulator **IM1** can be used in the long arm **Arm_l** to block the **P_r'** pulse of the T-P encoded photons **12c'**, and at least another one intensity modulator **IM1** can be used in the short arm **Arm_s** the unbalanced PM-based interferometer **23r'** to block the **P₀'** pulse of the T-P encoded photons **12c'**.

Lastly, a modulator which is not polarization sensitive can be used at the output of the T2H photon states converters disclosed herein, for blocking the photons at t_0 and t_2 , and transmitting only the photons at t_1 , thereby obtaining pure polarization encoded data.

These configurations have the advantage over standard pure-polarization state photon encoders that the time-bin and phase encoded data can be transmitted over substantially long distances of the optical fibers **12o'**, until it is required to convert them into the pure or hybrid polarization state encoded photons *e.g.*, for free space transmission. These configurations utilizing active components also eliminate the need to secure the location in which the T2H converter is mounted, since information is not encoded by the active components. Particularly, though some of the T2H converter embodiments hereof have active elements, the information regarding the encoded states that are transmitted by the system is not required for their operation and thus remain concealed. Therefore, no information is revealed to an adversary during the T2H photon states conversion, and the T2H conversion unit doesn't need to be secured like the quantum encoding components (**12u**).

The modulation applied in **Fig. 4A** by the 1:2 optical switch or intensity modulator **23s**, and in **Fig. 4B** by intensity modulators **IM1,IM2**, can be carried out periodically in accordance with the photon transmission frame-rate, and regardless of the actual data being transmitted. Different synchronization techniques can be applied to get the transmitter frequency, and some timing calibration may be required to precisely set the switching times.

Fig. 4C shows a T2H converter **37** utilizing an intensity modulator **IM** to selectively block the **St₀** and **St₂** optical signals at the output of the imbalanced interferometer **23r'**, and permit passage of the **St₁** optical signal through the output stage **25t**. The driver unit **D5** can be accordingly configured to periodically block the **St₀,St₂** optical signals, such that only the pure polarization encoded data **St₁** emerges out of the T2H converter **37**.

Fig. 5 illustrates a pure-polarization fiber-based QKD encoder **50** according to possible embodiments. There are various possible techniques to generate polarization states within optical fibers. The following polarization states generation technique requires only to rotate the frame of reference (the plane formed in 3D space by the H and V polarization vectors) for aligning the QKD transmitter and receiver systems to the H and V basis. The phase difference

between the optical signals in both of the arms **Arm₁**, **Arm₂** that forms the superposition states can be compensated between the H and V axes without moving parts, as illustrated in **Fig. 7**. In possible embodiments, the frame of reference can be aligned either by physically rotating the output PM fiber, or by rotating the receiver's aperture, or by using a half wave-plate phase
 5 retarder. It is noted that in this embodiment the optical signals propagating through the arms **Arm₁**, **Arm₂** of the balanced interferometer **58** are combined without interference due to their orthogonal polarization orientation.

The QKD encoder **50** shown in **Fig. 5** comprises PM input (**12o'**) and intermediate interferometric (**23r'**) stages, and an output stage that can be configured as either PM or non-
 10 PM. The QKD encoder **50** comprises a balanced interferometer **58** coupled to a light (*e.g.*, continuous wave/CW or pulsed laser) source **12s** configured to generate coherent linearly polarized optical signals. The intensity modulators **IM1**, **IM2** of the QKD encoder **50** shown in **Fig. 5** are configured to encode the data, and/or carve the optical pulses and encode the amplitude and phase data, onto optical signals generated by a plain laser source (either CW or
 15 pulsed) **12s** by respective driver units **D1**, **D2** thereof *e.g.*, with respective delay times **DL1**, **DL2**. The electrical delays **DL1**, **DL2** of the respective driver units **D1**, **D2** are configured to optimize the overlap (in time) of the optical signals propagating in the arms **Arm₁**, **Arm₂** and combined at the output of the balanced interferometer **58**.

The linearly (*e.g.*, horizontally) polarized optical signals received from the light source
 20 **12s** via the PM-based input stage is split (*e.g.*, 50:50 ratio) by the non-polarizing PM beam splitter into (*e.g.*, 50:50 ratio) the arms **Arm₁**, **Arm₂** of the PM PM interferometer **23r'**.

The intensities of the components of the polarized optical signals propagating along the arms **Arm₁**, **Arm₂** are modulated by their respective intensity modulators **IM1**, **IM2** according to the driving signals generated by their respective driver units **D1**, **D2**. The phase of the
 25 intensity modulated polarized optical signal component propagating along at least one of the arms is further shifted by the shift (*e.g.*, $\lambda/2$ waveplate) retarder **23w**, such that the polarity orientations of the optical signal components in the arms **Arm₁**, **Arm₂** are perpendicular one with respect to the other.

The intensity modulated and orthogonally polarized optical signal components in the
 30 arms **Arm₁**, **Arm₂** are combined at the polarization PM combiner **24''** into the output stage for transmission of polarized states encoded photons **25t** *e.g.*, over FSO. Accordingly, in this configuration there is only one time bin, which is the pure polarization state that emerges from the combiner **24''** at the output of the interferometer **58**. The **DL1**, **DL2** functionality of the

driver unit **D1,D2** are configured to accurately overlap the H and V polarized optical signals from the arms of the balanced interferometer **58**.

The QKD encoder **50** can be configured to generate all quantum states required for decoy-state BB84 implementations, which typically include different amplitudes of the $|H\rangle$, $|V\rangle$, $|+\rangle$, $|-\rangle$ ($|R\rangle$ and $|L\rangle$ polarizations can also be used as well) and the $|vacuum\rangle$ states. Optionally, but in some embodiments preferably, one or both of the intensity modulators **IM1,IM2** is a Mach-Zehnder intensity modulator. **Table 11** presents voltage levels that can be generated by the **D1,D2** driver units of the intensity modulators **IM1,IM2** for generating polarized encoded photons according to possible embodiments. Other embodiments can include both amplitude and phase modulators in each arm.

In different modulator structures, including x-cut or z-cut structure, applying different voltage signs results in an π shift of the phase (opposite sign for the phase), thus generating the required diagonal (or circular) polarizations.

Table 11 – voltage levels generated by the drivers of the intensity modulators for generating polarized encoded photons

	IM_1	IM_2
$ H\rangle$	V	0
$ V\rangle$	0	V
$ p\rangle$	$V_{1/2}$	$V_{1/2}$
$ m\rangle$	$V_{1/2}$	$-V_{1/2}$

In some embodiments the bias voltage level applied to the intensity modulators **IM1,IM2** are configured such that the optical output power thereby affected when the V voltage level is applied by their driver units **D1,D2** is twice the optical output power thereby affected when the $V_{1/2}$ voltage level is applied *i.e.*, $IM_{Pout}(V)=2* IM_{Pout}(V/2)$. Other bias voltage levels V_d and $V_{d1/2}$ can be applied by the driver units **D1,D2** for generating decoy states.

Since the precise length of the optical fibers and control electronics wiring is hard to set to the sub nanosecond level, a (*e.g.*, tuneable) delay line mechanism can be applied to one (or both) of the driver units **D1,D2**.

Fig. 6 illustrates a photon processing setup **60** configured according to possible embodiments to convert pure-polarization state encoded photons into time-bin state encoded photons. The photon processing setup **60** generally comprises an input stage **12i** for receiving polarization state encoded photons, and a (*e.g.*, passive) converter stage **61** optically coupled to the input stage **12i** and configured to convert polarization state encoded photons into T-P

state encoded photons. The polarization state encoded photons **12i** received via the input stage are split by the polarization PM beam splitter **61p** of the converter stage **61** into two orthogonally (*e.g.*, vertically and horizontally) polarized components, directed into respective long and short arms **61l,61s** of the imbalanced interferometer. The input of the PBS **61p** is thus aligned with the H/V plane of the polarization state encoded photons **12i**. The (*e.g.*, vertically) polarized component in the long arm **61l** undergoes a 180° phase shift as it passes through the phase retarder **61w**, thereby converting its polarization into the orthogonal (*e.g.*, horizontal) polarization orientation of the polarized component in the short arm **61s**.

The optical signals from the long and short arms **61l,61s** are thus received at the beam combiner **61c** in the same polarization orientation, but in a time-difference/lag of τ seconds, wherein τ is the time difference between time-bins of the optical signals emerging from the long and short arms **61l,61s** of the imbalanced interferometer **61**. In possible embodiments the $|H\rangle$ polarized state photons are passed through the short arm **61s** and thereby converted into $|0\rangle$ T-P encoded state photons. The $|V\rangle$ polarized state photons are passed through the long arm **61l** and converted into $|1\rangle$ T-P encoded state photons. The diagonal $|H + V\rangle$ polarized state photons are converted into $|p\rangle$ T-P encoded state photons, and the diagonal $|H - V\rangle$ polarized state photons, that has an opposite phase between their H and V components, are converted into $|m\rangle$ T-P encoded state photons by combining the optical signal components from the long and short arms **61l,61s** at the beam combiner **61c**.

Optionally, but in some embodiments preferably, the photon processing setup **60** is further configured to detect the encoded states of the photons thereby processed. In such embodiments the photon processing setup **60** further comprises a photon encoding state analyzer stage **62** optically coupled to the converter stage **61** and configured generate optical signals indicative of the photon state encoding, and an output stage **63** optically coupled the photon encoding state analyzer stage **62** and configured to detect the encoding state of the processed photons.

In some embodiments the coupling between the converter stage **61** and the analyzer stage **62** is obtained using a significantly long optical fiber **61e** (*e.g.*, from few meters and up to few tens of kilometers, optionally hundred of meters, depending on the total attenuation the system can tolerate). This achieved in some embodiment using a single-mode optical fiber (SMF) for the coupling **61e**.

The H/V plane of the incoming polarization state encoded photons **12i** can be (*e.g.*, controllably or mechanically) aligned with the H/V plane of the polarization splitter **61p** at the

input of the imbalanced (*e.g.*, Mach Zehnder or Michelson) interferometer **61**. Assuming the polarization splitter **61p** splits the vertically polarized components of the incoming photons into the long arm **61l** and their horizontally polarized components into the short arm **61s**, then the horizontal (H) polarization orientation components from the short arm **61s** are converted into the 1st time-bin ($t = 0$), and the vertical (V) polarization orientation components from the long arm **61l** are converted into the 2nd time-bin ($t = \tau$). The $|H + V\rangle$ and the $|H - V\rangle$ polarization state photons obtained at the beam combiner **61c** are converted to the different phase superposition states, $|p\rangle$ and $|m\rangle$ as explained hereinabove and presented in Table 12.

Accordingly, the optical signals received at the combiner **61c** from the long and short arms of the imbalanced interferometer **61** are in the same polarization orientation, for generating the needed time-bin and phase photon encoding photon states transmitted for the analysis at the analyzer stage **62**. The non-polarizing (*e.g.*, 50:50 ratio) beam splitter **62p** splits the T-P states encoded photons from the converter stage **61** into the long and short arms **62l,62s** of the of the imbalanced (*e.g.*, Mach Zehnder or Michelson) interferometer **62**. The time-difference/lag between the long and short arms **62l,62s** is configured for τ seconds for properly combining the time-bins at the optical signals pulses of the T-P states encoded photons at the beam combiner (also non-polarizing splitter) **62c**.

The non-polarizing beam splitter **62c** is configured to (*e.g.*, 50:50 ratio) split the output optical signals from the converter stage **61** into two detection arms, each optically coupled to a respective (*e.g.*, single-photon avalanche diode) detector **SPAD1,SPAD2**. At the output stage **63** of the photon processing setup **60**, the accumulated phase of the $|p\rangle$ and $|m\rangle$ states is not controlled, but the $|p\rangle$ and $|m\rangle$ states are still orthogonal. The optical signals received by the detectors **SPAD1,SPAD2** and analyzed according to the photon time of arrivals and which of the **SPAD1,SPAD2** detectors they reached (as presented in Table 3).

As noted above, the converter stage **61** generating the time-bin and phase encoded photons may be located substantially remote from the analyser and output stages **62,63**. This property of the photon processing setup **60** is advantageous as it permits locating the sensitive QKD system far away from the passive optics (*e.g.*, FSO) and T2H converter. The phase at the analyser interferometer (ϕ_3) can be set to compensate for all of the accumulated phases *e.g.*, of the interferometers in the QKD transmitter (ϕ_1) and in the Converter (ϕ_2). This can be done by laser wavelength fine-tune or by interferometer thermal control, in a closed loop with the SPAD measured values (by QBER minimization for example).

Having one phase compensation device to compensate for the phases drift of the superposition states by wavelength tuning and without moving parts, both for the time-bin and polarization bases is another advantage of this technique. It means that only one feedback loop for the phases is required, and no $\lambda/4$ waveplates or similar hardware is required. It makes this solution more robust, simple, low cost and secure.

Table 12 – conversion of polarization photon encoding states into T-P photon encoding states

Polarization state before the converter	Timebin and phase state after the converter
$ H\rangle$	$ 0\rangle$
$ V\rangle$	$ 1\rangle$
$ H\rangle + e^{i\theta} V\rangle$	$ p\rangle$
$ H\rangle - e^{i\theta} V\rangle$	$ m\rangle$

Embodiments hereof may utilize different half-wavelength waveplate implementations. There are a few ways to implement fiber-based half wavelength waveplate. For example, there are devices that apply the desired birefringence property of waveplates by stress and/or twisting of the optical fiber, there are free-space optical elements (*e.g.*, quartz or mica optical windows) with intrinsic birefringence, packed inline with the optical fiber. When using PM-based fibers, when the optical signal traveling through the optical fiber is aligned with the fast axis, for example, a half wavelength waveplate may be required to rotate the optical signal to the slow axis of the PM fiber.

In some embodiment this is implemented by fusing two PM-based optical fibers with 90° rotation, to directly transfer optical signals aligned with the fast-axis light to the slow-axis of the optical fiber. This method achieves the effect of the waveplate without the requirement of any additional optical elements on the optical path. Other fusing angles can be used to affect other polarization orientations. By busing fast to slow axis, the different propagation speed can be compensated if required.

Possible implementations of the polarization plane aligner **20** shown in **Fig. 2B** are described hereinabove. In order to transform an arbitrary polarization state to any desired polarization state, any combination of half and quarter waveplates can be used, which may be configured as either fiber-based or free space optics waveplates. The T2H converters **32**, **33** and **34**, of **Figs. 3C**, **3D** and **3E**, may require stabilization of the phase of the optical signals to generate the diagonal state photon polarizations. This is because if the phase is not controlled, other elliptical polarizations are likely to be obtained. However, the orthogonality of the

encoded states will still be maintained. A polarization plane aligner **20** *e.g.*, located within the QKD transmitter, receiver, or anywhere along the optical path therebetween, can compensate both for the polarization rotations within the transmitter and on the optical path, as long as the rate of polarization changes is slow *e.g.*, smaller than π radians/second, thereby simplifying the transmitter operation.

Fig. 7 demonstrates a control scheme **77** configured to compensate phase and/or polarization drifts between the transmitter **12** and receiver **11** systems. The control unit **11u** of the receiver system **11** is configured to receive from the detectors (*e.g.*, **SPAD1** and **SPAD2** in **Fig. 6**) **63** data/signal of the encoded data of the optical signal **St₁**, and of the orthogonal (H/V) polarization states of the optical signal **St₀** and **St₂**. A polarization control module can be used in the control unit **11u** to process and analyze the orthogonal (H/V) polarization states of the optical signal **St₀** and **St₂**, and determine based thereon polarization orientation corrections, if so need. The control unit **11u** can then generate control signals **20c** for either the polarization plane aligner **20**, or other angular position rotary adjustment means at the transmitter or receiver, in order to correct any polarization orientation misalignments between the transmitter and receiver systems **12,11**.

The control unit **11u** can further include a phase control module configured to process the optical signal **St₀**, **St₁**, and/or **St₃** and determine based thereon phase drifts of the received photons. The control unit **11u** can be configured to generate control signals/date **20g** to correct phase drifts by adjusting the wavelength of light source **12s** at the transmitter system **12**. For example, the control signals/date **20g** can be transmitted to the transmitter system **12** over the standard communication link **10s**, that is further adapter in possible embodiment for system control. The control unit **12u** of the transmitter comprises in some embodiments a wavelength control module configured to receive the control signals/date **20g** from the receiver **11** accordingly control a wavelength tuning unit **12w** of the light source **12s**.

In order to align the polarization plane between the QKD transmitter and QKD receiver, feedback loops can be used, or other ways, for relative polarization shift adjustments. In possible embodiment the polarization plane aligner **20** is configured to receive the information required to align the polarization state between the QKD transmitter and the QKD receiver. For example, as follows:

1. The QKD transmitter can be configured to transmit (in addition to the quantum communication beam) an alignment laser beam with high enough power to be measured on the QKD receiver side. If the medium (*e.g.*, the atmosphere) between the QKD transmitter and QKD receiver is non-birefringent, any wavelength supported by the

optical components can be used for the alignment laser beam. If the medium is birefringent, as with realistic optical fibers, the wavelength of the alignment beam is similar to that of the data-carrying optical signal/laser.

At the QKD receiver side, the polarization state is mapped, and the feedback for correction of the polarization is transferred to the polarization plane aligner **20**.

2. In possible embodiments the QKD receiver is configured to transmit the alignment laser beam to the QKD transmitter. The QKD transmitter can have a polarization state mapping system (*e.g.*, polarimeter), configured to send feedback to the polarization plane aligner **20** to get the required polarization state at the QKD receiver side.
3. With free space optical links, either on earth or in space, the relative orientation of the transmitter and receiver can be pre-calibrated or measured (by an accelerometer for example). The calculated relative polarization shift is then corrected by the polarization plane aligner **20**.
4. Without sending additional laser light, the polarization can be controlled to minimize the bit error rate *e.g.*, using feedback data/signals from the detection system at the receiver during the QKD parameter estimation stage.

In possible embodiments the passive T2H converters disclosed herein are employed for point-to-Multipoint (P2MP) QKD network communication, as explained hereinbelow.

One of the challenges in implementing point-to-Multipoint (P2MP) QKD networks is that in many system designs the calibration of the systems is pair-wise. **Figs. 8A** and **8B** illustrate two P2MP configurations, with a 1:64 passive optical network (PON) network, for example. **Fig. 8A** shows a P2MP PON network **70** having a single QKD receiver **70r** and multiple QKD transmitters **70t**, and **Fig. 8B** shows a P2MP PON network **71** having a single QKD transmitter **70t** and multiple QKD receivers **70r**.

For time-bin and phase photon states coding, the unbalanced interferometer (*e.g.*, **62** in **Fig. 6**) which is located on Bob's (*i.e.*, QKD receiver **70r**) side determines the time difference τ between the two transmitted time-bins (P_0, P_τ) of the T-P encoded photons, and therefore the clock frequency of the QKD transmitter **70t**. When there is a need to connect one QKD receiver **70r** to multiple QKD transmitters **70t**, as exemplified in **Fig. 8A**, it can work well. With a single QKD receiver **70r**, all QKD transmitters **70t** usually require the management of the transmission time windows of the different QKD transmitters **70t** in order to form time-division-multiplexing (TDM).

However, when there is a need to connect a single QKD transmitter **70t** to multiple QKD receivers **70r**, as exemplified in **Fig. 8B**, the stabilization of the single QKD transmitter

70t (laser/light source) to multiple interferometers QKD receivers 70r becomes a challenge. In the passive T2H converter embodiments disclosed herein, the unbalanced interferometer is typically located at the QKD transmitter 70t side. Therefore the single QKD transmitter 70t can determine the clock frequency for the multiple QKD receivers 70r, enabling the operation of such P2MP network. All QKD receivers 70r can measure simultaneously, without the TDM requirement, making the network deployment and management much simpler: the QKD receivers 70r can be connected and disconnected without affecting the rest of the connected QKD receivers 70r.

Relative terms such as "lower," "upper," "horizontal," "vertical," "above," "below," "up," "down," "top" and "bottom", as well as derivatives thereof (e.g., "horizontally," "downwardly," "upwardly," etc.), and similar adjectives in relation to orientation of the described elements/components refer to the manner in which the illustrations are positioned on the paper, not as any limitation to the orientations in which these elements/components can be used in actual applications. It is also noted that terms such as first, second,... etc. may be used to refer to specific elements disclosed herein without limiting, but rather to distinguish between the disclosed elements.

It should also be understood that throughout this disclosure, where a process or method is shown or described, the steps/acts of the method may be performed in any order and/or simultaneously, and/or with other steps/acts not-illustrated/described herein, unless it is clear from the context that one step depends on another being performed first. In possible embodiments not all of the illustrated/described steps/acts are required to carry out the method.

Those skilled in the art will understand and appreciate that the depicted methods may alternatively, or additionally, be illustrated as a series of interrelated states via a state diagram and/or events that can be implemented by a state machine. Additionally, or alternatively, the methods disclosed herein can be stored on an article of manufacture *e.g.*, program instructions and/or data stored on storage media and executable by a computer device, to facilitate implement the method by computing devices.

Those of skill in the art would appreciate that items such as the various illustrative blocks, modules, elements, components, methods, operations, steps, and algorithms described herein may be implemented as hardware or a combination of hardware and computer software. To illustrate the interchangeability of hardware and software, items such as the various illustrative blocks, modules, elements, components, methods, operations, steps, and algorithms have been described generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design

constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application.

In an embodiment where the invention is implemented using software, the software can be stored in a computer program product and loaded into the computer system using the
5 removable storage drive, the memory chips or the communications interface. The control logic (software), when executed by a control processor, causes the control processor to perform certain functions of the invention as described herein.

In another embodiment, features of the invention are implemented primarily in hardware using, for example, hardware components such as application specific integrated
10 circuits (ASICs) or field-programmable gated arrays (FPGAs). Implementation of the hardware state machine so as to perform the functions described herein will be apparent to persons skilled in the relevant art(s). In yet another embodiment, features of the invention can be implemented using a combination of both hardware and software.

As described hereinabove and shown in the associated figures, the present invention
15 provides QKD system configurations useful for FSO communication, and related methods. While particular embodiments of the invention have been described, it will be understood, however, that the invention is not limited thereto, since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings. As will be appreciated by the skilled person, the invention can be carried out in a great variety of ways, employing more than
20 one technique from those described above, all without exceeding the scope of the claims.

CLAIMS:

1. A photon state polarization converter comprising:
an imbalanced interferometer configured to generate the following three optical signal pulses responsive to time-bin and phase states encoded photons thereby received: (i) a first
5 optical pulse signal responsive to a first time-bin of said time-bin and phase states encoded photon emerging through a short arm of said imbalanced interferometer; (ii) a second optical pulse signal responsive to an interference pattern between said first time-bin emerging through a long arm of said imbalanced interferometer and a second time-bin of said time-bin and phase states encoded photon emerging through said short arm; and (iii) a third optical pulse signal
10 responsive to said second time-bin emerging through the long arm of said imbalanced interferometer; and
at least one polarization orientation manipulating device configured to affect orthogonal polarization orientations to light components from said imbalanced interferometer and thereby generate hybrid time-bin and polarization states encoded photons.
- 15 2. The photon state polarization converter of claim 1 comprising two polarization arms optically coupled to the imbalanced interferometer and configured for generating the two orthogonally polarized optical signals.
3. The photon state polarization converter of claim 2 wherein each one of the polarization arms comprises a respective polarization orientation manipulating device.
- 20 4. The photon state polarization converter of claim 2 comprising a half wavelength phase retarder in one of the polarization arms.
5. The photon state polarization converter of claim 1 wherein the time-bin and phase states encoded photons have a defined linear polarization orientation, and wherein said photon state polarization converter comprises a half wavelength phase retarder in one of the arms of the
25 imbalanced interferometer.
6. The photon state polarization converter of claim 1 wherein the time-bin and phase states encoded photons have a defined diagonal polarization orientation, and wherein said photon state polarization converter comprises a half wavelength phase retarder in one of the arms of the imbalanced interferometer and a polarizing beam splitter for transmitting said time-bin and
30 phase states encoded photons into the long and short arms of the imbalanced interferometer.
7. The photon state polarization converter of claim 1 wherein the time-bin and phase states encoded photons have a defined linear polarization orientation, and wherein said photon state polarization converter comprises a half wavelength phase retarder in one of the arms of the

imbalanced interferometer and a polarizing beam combiner for combining optical signals emerging from the long and short arms of the imbalanced interferometer.

8. The photon state polarization converter of claim 7 comprising an optical switch device configured to selectively transmit the first time-bin of the time-bin and phase states encoded
5 photon into the long arm of the imbalanced interferometer and the second time-bin of the time-bin and phase states encoded photon into the short arm of the imbalanced interferometer.

9. The photon state polarization converter of claim 7 comprising a first intensity modulator configured to selectively block passage of the first time-bin of the time-bin and phase states encoded photon through the short arm of the imbalanced interferometer, and a
10 second intensity modulator configured to selectively block passage of the second time-bin of said time-bin and phase states encoded photon through the long arm of the imbalanced interferometer.

10. The photon state polarization converter of claim 9 comprising a first driver unit configured to operate the first intensity modulator to periodically block passage of the first
15 time-bin of the time-bin and phase states encoded photon through the short arm, and a second driver unit configured to operate the second intensity modulator to periodically block passage of the second time-bin of the time-bin and phase states encoded photon through the long arm.

11. The photon state polarization converter of claim 7 comprising an intensity modulator configured to selectively block passage of the first and third optical pulse signals through an
20 output of the imbalanced interferometer.

12. A quantum communication system comprising transmitter and receiver systems configured to communicate over a free space medium, said transmitter system comprising a quantum transmitter configured to generate time-bin and phase states modulated photons, and the photon state polarization converter of any one of the preceding claims optically coupled
25 said quantum transmitter for converting time-bin and phase states encoded photons thereby generated into hybrid time-bin and polarization states encoded photons for transmission to the receiver system over said free space medium.

13. The quantum communication system of claim 12 wherein the quantum transmitter is mounted in a secure location relatively remote to the photon state polarization converter and
30 optically coupled thereto by one or more optical fibers.

14. The quantum communication system of claim 12 or 13 wherein the receiver system comprises a quantum receiver optically coupled to a photon state polarization converter configured to convert hybrid time-bin and polarization states photons received over the free space medium into time-bin and phase states encoded photons.

15. The quantum communication system of claim 14, wherein the quantum receiver is mounted in a secure location relatively remote to said photon state polarization converter and optically coupled thereto by one or more optical fibers.

16. A polarization photon states encoder comprising: a coherent light source of a defined linear polarization orientation; an interferometer optically coupled to said coherent light source and configured with a polarizing beam combiner for combining optical signals emerging from arms thereof; first and second modulators configured to respectively modulate amplitude and phase of optical signals passing through said arms; and a half wavelength phase retarder configured to shift polarization orientation of optical signals passing through one of said arms.

17. The polarization photon states encoder of claim 16 comprising separate amplitude and phase modulators in each of the arms.

18. The polarization photon states encoder of claim 16 comprising a single intensity modulator in each of the arms configured to modulate both amplitude and phase of the optical signals.

19. A quantum communication system comprising transmitter and receiver systems configured to communicate over free space medium or optical fibers, said transmitter system comprising a quantum transmitter comprising the polarization photon states encoder of any one of claims 16 to 18.

20. A method of converting photon state polarization, the comprising passing time-bin and phase states encoded photons through an imbalanced interferometer configured to generate a first optical pulse signal responsive to a first time-bin of said time-bin and phase states encoded photon emerging through a short arm of said imbalanced interferometer, a second optical pulse signal responsive to an interference pattern between said first time-bin emerging through a long arm of said imbalanced interferometer and a second time-bin of said time-bin and phase states encoded photon emerging through said short arm, and a third optical pulse signal responsive to said second time-bin emerging through the long arm of said imbalanced interferometer, and setting orthogonal polarization orientations to light components from said imbalanced interferometer and thereby generating hybrid time-bin and polarization states encoded photons.

21. The method of claim 20 comprising setting one light components from the imbalanced interferometer into a horizontal orientation and another light component therefrom into a vertical polarization orientation.

22. The method of claim 20 comprising applying a half wavelength phase shift to one the light components from the imbalanced interferometer.

23. The method of claim 20 wherein the time-bin and phase states encoded photons have a defined linear polarization orientation, and wherein the method comprising applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer.

5 24. The method of claim 20 wherein the time-bin and phase states encoded photons have a defined diagonal polarization orientation, and wherein the method comprising splitting the time-bin and phase states encoded photons into orthogonally polarized light components into the long and short arms of the imbalanced interferometer and applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer.

10 25. The method of claim 20 wherein the time-bin and phase states encoded photons have a defined linear polarization orientation, and wherein the method comprising applying a half wavelength phase shift to optical signals passing through one of the arms of the imbalanced interferometer and combining orthogonally polarized optical signals emerging from the long and short arms of the imbalanced interferometer.

15 26. The method of claim 25 comprising selectively transmitting the first time-bin of the time-bin and phase states encoded photon into the long arm of the imbalanced interferometer and the second time-bin of the time-bin and phase states encoded photon into the short arm of the imbalanced interferometer.

20 27. The method of claim 25 comprising selectively blocking passage of the first time-bin of the time-bin and phase states encoded photon through the short arm of the imbalanced interferometer, and selectively blocking passage of the second time-bin of said time-bin and phase states encoded photon through the long arm of the imbalanced interferometer.

28. The method of claim 17 comprising selectively blocking passage of the first and third optical pulse signals through an output of the imbalanced interferometer.

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