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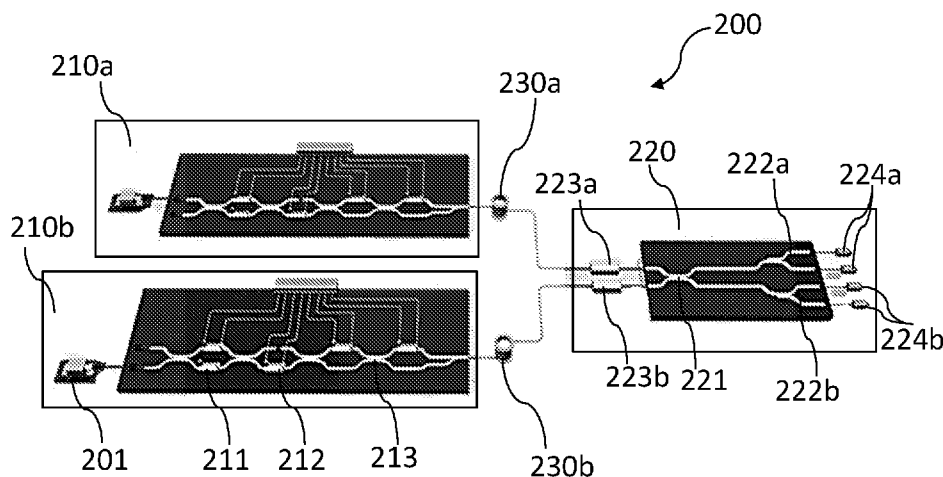


Figure 4

(57) Abstract: Embodiments of the invention provide a chip-based system and apparatuses for measurement-device-independent (MDI) quantum key distribution (QKD). The system comprises two transmitters and a receiver, wherein each of the two transmitters is communicably connectable to the receiver and comprises a first modulator, a second modulator, and a third modulator which are integrated onto a silicon photonic chip, wherein: the first modulator is configured to receive input laser pulses from a laser source and generate signal states and decoy states by modifying laser intensity of the received input laser pulses; the second modulator is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator, and the third modulator is configured to generate polarization states based on the signal states and the decoy states modulated by the second modulator.



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SYSTEM AND APPARATUSES FOR MEASUREMENT-DEVICE-INDEPENDENT QUANTUM KEY DISTRIBUTION

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Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 10202002446V, filed 17 March 2020, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] The invention relates to measurement-device-independent (MDI) quantum key distribution (QKD), more specifically, a system, transmitter, and receiver for MDI QKD.

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Background

[0003] QKD promises a highly secured way of sharing secret keys between two individuals. It has been successfully demonstrated in fibre, free-space, and satellite platforms. However, conventional QKD systems are unable to guarantee theoretical unconditional security due to imperfect implementations of QKD in practical scenarios. For example, an eavesdropper might be able to remotely control single-photon detectors in a QKD system and steal a full secret key without leaving a trace. To counter such side-channel attacks, MDI-QKD, which obviates any assumptions made for the measurement device, has been proposed and demonstrated. The MDI-QKD architecture is naturally suited for multi-user QKD networks, since the most expensive and intricate component, i.e., the measurement device, can be placed in an untrusted relay and shared among many QKD users. Therefore, MDI-QKD has been widely recognized as a promising quantum communication technology for star-type secured networks.

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[0004] Conventional MDI-QKD systems rely entirely on bulky and expensive optical setups that present great challenges for system scaling and integration, hence are difficult

to deploy for real-world applications. In contrast, silicon photonics technology offers many unparalleled benefits including small size, low cost, low power consumption, and well-established batch fabrication techniques. Over the past few years, much effort has been made for chip-level implementation of discrete-variable QKD (DV-QKD) and continuous-variable QKD (CV-QKD). In these schemes, silicon photonic chip-based QKD empowers quantum communication systems that are not only phase-stable and easily tailorable, but also straightforward to realize precise time sequence alignment via chip-level temperature control, thereby enabling high-speed QKD without significant temporal drift.

[0005] Recently, several photonic chips for MDI QKD have been fabricated on different substrates, e.g., silica, In, and silicon. However, these works only demonstrated hybrid chip-based MDI QKD systems with either two transmitter chips plus a fiber-based server or two fiber-based transmitters plus a silica-substrate-based server chip. It, therefore, remains a challenge to provide a long-desired, low-cost, and scalable quantum communication network using an all-chip-based MDI QKD system.

Summary of Invention

[0006] Various embodiments of the invention provide an all chip-based system and apparatuses for MDI QKD, which have great potential for scalable and cost-effective secured communications.

[0007] According to a first aspect of the invention, some embodiments of the invention provide an all-chip based system for MDI QKD, the system may include two transmitters and a receiver, wherein each of the two transmitters is communicably connectable to the receiver and comprises a first modulator, a second modulator and a third modulator which are integrated onto a silicon photonic chip, wherein the first modulator is configured to receive input laser pulses from a laser source and generate signal states and decoy states by modifying laser intensity of the received input laser pulses; the second modulator is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator, and the third modulator is configured to generate polarization states based on the signal states and the decoy states modulated by the second modulator.

[0008] According to the first aspect of the invention, in one embodiment of the invention, the chip-based receiver may comprise a beam splitter (BS), a first path-to-polarization converter (PPC), and a second PPC, wherein the BS and the first and the second PPCs are integrated onto a silicon photonic chip to perform Bell state measurement on the polarization states received from the two transmitters.

[0009] According to a second aspect of the invention, some embodiments of the invention provide a chip-based transmitter which may comprise a first modulator, a second modulator, and a third modulator which are integrated onto a silicon photonic chip, wherein the first modulator is configured to receive input laser pulses from a laser source and generate signal states and decoy states by modifying laser intensity of the received input laser pulses; the second modulator is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator, and the third modulator is configured to generate polarization states based on the signal states and the decoy states modulated by the second modulator.

[0010] According to a third aspect of the invention, some embodiments of the invention provide a chip-based receiver which may comprise a beam splitter (BS), a first polarizing beam splitter (PBS), and a second PBS, wherein the BS, and the first and the second PBSs are integrated onto a silicon photonic chip to perform Bell state measurement on polarization states received from two transmitters, wherein each transmitter is designed according to some embodiments of the invention.

[0011] The fully chip-based MDI-QKD system and apparatuses proposed in embodiments of the invention promise great potential for scalable and cost-effective secured communications, making a giant step forward towards highly integrated quantum communication networks.

Brief Description of the Drawings

[0012] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description,

various embodiments of the invention are described with reference to the following drawings, in which:

[0013] Figure 1 shows a schematic view of a system for MDI QKD, according to some embodiments of the invention.

5 [0014] Figure 2A shows a schematic view of the chip-based transmitter in the system as shown in Figure 1, according to some embodiments of the invention.

[0015] Figure 2B shows a schematic view of the third modulator of the transmitter as shown in Figure 2A, according to some embodiments of the invention.

10 [0016] Figure 3A shows a schematic view of the receiver, as shown in Figure 1, according to some embodiments of the invention.

[0017] Figure 3B shows a schematic view of the receiver, as shown in Figure 1, according to some other embodiments of the invention.

[0018] Figure 4 shows a schematic view of a chip-based system for MDI QKD, according to a first embodiment of the invention.

15 [0019] Figures 5A and 5B illustrate optical micrographs of a transmitter chip and a receiver chip, as shown in Figure 4, respectively.

[0020] Figure 5C shows the transmitter chip, as shown in Figure 4, packaged on a printed circuit board (PCB).

20 [0021] Figure 6A shows a plot illustrating a simulated transmission in a mode combiner of a PPC, according to the first embodiment of the invention, with field propagations shown in insets of Figure 6A.

[0022] Figure 6B shows a plot illustrating a simulated transmission in a polarization rotator of the PPC, according to the first embodiment of the invention, with field propagations shown in insets of Figure 6B.

25 [0023] Figure 6C shows an optical micrograph of the mode combiner in the PPC, according to the first embodiment.

[0024] Figure 6D shows a plot illustrating a measured transmission spectrum of the PPC for TE₀ input at upper and lower ports of the mode combiner, according to the first embodiment.

30 [0025] Figure 7 shows a plot illustrating on-chip polarization state preparation in one experiment, according to one embodiment of the invention.

[0026] Figure 8 shows a plot illustrating a comparison of theoretical and experimental results of a secure key rate per pulse versus different transmission distances with various types of single-photon detectors, according to some embodiments of the invention.

5 Detailed Description

[0027] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details, and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized, and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0028] Embodiments described in the context of one of the methods or apparatuses are analogously valid for the other methods or apparatuses. Similarly, embodiments described in the context of a method are analogously valid for an apparatus, and vice versa.

[0029] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0030] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0031] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0032] Figure 1 shows a schematic view of a system 100 for MDI QKD according to some embodiments of the invention. The system 100 may include two chip-based transmitters 110a and 110b and a chip-based receiver 120. Each of the two transmitters 110a and 110b is communicably connectable to the receiver 120.

[0033] Figure 2A shows a schematic view of the chip-based transmitter 110a or 110b in the system 100 according to some embodiments of the invention. Referring to Figure 2A, the transmitter 110a or 110b may include a first modulator 111, a second modulator 112, and a third modulator 113 which are integrated onto a silicon photonic chip, i.e. the transmitter chip, wherein the first modulator 111 is configured to receive input lasers from a laser source 101 and generate signal states and decoy states by modifying laser intensity of the received input laser pulses; the second modulator 112 is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator 111, and the third modulator 113 is configured to generate polarization states based on the signal states and the decoy states modulated by the second modulator 112.

[0034] In some embodiments, the first modulator 111 may include a Mach-Zehnder interferometer (MZI) modulator. The laser source 101 may be a pulse-modulated laser or any other appropriate laser source as would be known by a person skilled in the art, e.g., a pulse-modulated 1542.3815 nm frequency-locked laser. The laser source 101 may be coupled into the silicon waveguide on the transmitter 110a or 110b through a grating coupler. It should be noted that the first modulator 111 may generate a signal state or a decoy state at a point of time based on an input laser from the laser source 101.

[0035] In some embodiments, the second modulator 112 may include a phase modulator which is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator 111 to guarantee a phase randomization assumption.

[0036] In some embodiments, as shown in Figure 2B which is a schematic view of the third modulator 113 according to some embodiments of the invention, the third modulator 113 may include a MZI modulator 113a, two phase shifters 113b and 113c and a path-to-polarization converter (PPC) 113d, wherein the MZI modulator 113a is configured to generate a first transverse electric (TE) mode of a first waveguide, e.g. an upper waveguide of the MZI modulator 113a, and a second TE mode of a second waveguide, e.g. a lower waveguide of the MZI modulator 113a, based on the signal states and decoy states modulated by the second modulator 112 and adjust an intensity difference between the first TE mode and the second TE mode; the two phase shifters 113b and 113c are configured to receive the first TE mode and the second TE mode respectively and adjust a phase

difference between the first TE mode and the second TE mode; and the PPC 113d is configured to generate a polarization state based on the first TE mode and the second TE mode. Further, the transmitter chip of each transmitter 110a or 110b may further include an adiabatic tapered waveguide coupler configured to couple the generated polarization state to the receiver 120. Preferably, the adiabatic tapered waveguide coupler may have a rectangular cross-sectional shape of approximately 200nm by 220nm at one end of the adiabatic tapered waveguide coupler to minimize the polarization-dependent loss (PDL). According to one embodiment, the PPC 113d may include a polarization rotator configured to convert one of the first TE mode and the second TE mode into a transverse magnetic (TM) mode; and a mode combiner configured to combine the TM mode and the first TE mode or the second TE mode which is not converted to generate the polarization state.

[0037] Alternatively, in some embodiments, the PPC 113d of the third modulator 113 and the adiabatic tapered waveguide coupler may be replaced with a two-dimensional (2D) grating coupler. That is to say, the third modulator 113 may include a MZI modulator, two phase shifters and a 2D grating coupler. The functions of the MZI modulator and the two phase shifters are the same as those of the MZI modulator 113a, and the two phase shifters 113b and 113c respectively, which will not be repeated again here. The 2D grating coupler is configured to generate a polarization state based on the first TE mode and the second TE mode. Further, the 2D grating coupler is also configured to couple the generated polarization state to the receiver 120.

[0038] In some embodiments of the invention, the transmitter chip of the transmitter 110a or 110b may be fabricated on a silicon-on-insulator (SOI) wafer. The wafer may have a top silicon layer of 220nm and a buried oxide layer (BOX) of 3 μm .

[0039] In some embodiments of the invention, as shown in Figure 3A which is a schematic view of the receiver 120 according to some embodiments of the invention, the chip-based receiver 120 may include a beam splitter (BS) 121, a first polarizing beam splitter (PBS) 122a and a second PBS 122b, wherein the BS 121, and the first PBS 122a and the second PBS 122b are integrated onto a silicon photonic chip, i.e. a receiver chip, to perform Bell state measurement on the polarization states received from the two transmitters 110a and 110b. Specifically, the BS 121 is configured to perform two-photon interferometry/Hong-Ou-Mandel (HOM) interferometry; the two PBSs 122a and 122b are configured to measure

horizontal and vertical polarization states, and the BS 121, and the two PBSs 122a and 122b jointly achieve the Bell state measurement for secret key generation.

[0040] Alternatively, in some other embodiments, the first PBS 122a and the second PBS 122b may be replaced with a first PPC 122'a and a second PPC 122'b respectively, as shown in Figure 3B. Specifically, the chip-based receiver 120 may include a BS 121, a first PPC 122'a and a second PPC 122'b, wherein the BS 121, and the first and the second PPCs 122'a and 122'b are integrated onto a silicon photonic chip to perform Bell state measurement on the polarization states received from the two transmitters 110a and 110b. Specifically, the BS 121 is configured to perform two-photon interferometry/Hong-Ou-Mandel (HOM) interferometry; the two PPCs are configured to measure horizontal and vertical polarization states, and the BS and the two PPCs 122'a and 122'b jointly achieve the Bell state measurement for secret key generation.

[0041] In some embodiments, each of the two transmitters 110a and 110b may be communicably connected to the receiver 120 through a lensed fiber or a standard single mode fiber.

[0042] In some embodiments, referring to Figures 3A and 3B, the receiver 120 may further include two electrical polarization controllers (EPCs) 123a and 123b configured to receive the polarization states from the two transmitters 110a and 110b respectively, and perform polarization drift compensation on the polarization states to maximize Hong-Ou-Mandel (HOM) interference between the polarization states. It should be noted that the two EPCs 123a and 123b are off-chip components of the receiver 120.

[0043] In some embodiments, referring to Figures 3A and 3B, the receiver 120 may further include a first pair of single-photon detectors (SPDs) 124a and a second pair of SPDs 124b, wherein the first pair of SPDs 124a is configured to detect photons from the first PBS 122a or the first PPC 122'a of the receiver 120, and the second pair of SPDs 124b is configured to detect photons from the second PBS 122b or the second PPC 122'b of the receiver 120. It should be noted that the first pair of SPDs 124a and the second pair of SPDs 124b are off-chip components of the receiver 120.

[0044] In some embodiments of the invention, the receiver 120 may be fabricated on a silicon-on-insulator (SOI) wafer. The wafer may have a top silicon layer of 220nm and a buried oxide layer (BOX) of 3 μm .

[0045] In some embodiments, the system 100 may further include a fiber-based polarization alignment system configured to calibrate the two transmitters 110a and 110b.

[0046] Figure 4 shows a schematic view of a chip-based system 200 for MDI QKD according to a first embodiment of the invention. The system 200 includes two chip-based transmitters, i.e., Alice 210a and Bob 210b, and a chip-based receiver, i.e., Charlie 220.

[0047] As shown in Figure 4, each of Alice 210a and Bob 210b includes a laser source 201, an intensity/decoy state modulator 211, a phase modulator 212, and a polarization modulator 213, wherein the intensity modulator 211, the phase modulator 212, and the polarization modulator 213 are integrated onto a silicon photonic chip, i.e., the transmitter chip. The laser source 201 is configured to provide input lasers to the intensity modulator 211. In this embodiment, the laser source 201 is a pulse-modulated 1542.3815-nm frequency-locked laser which is coupled into the silicon waveguide on the silicon photonic chip of the transmitter, i.e., Alice 210a or Bob 210b, through a grating coupler. The intensity modulator 211 includes an MZI modulator which is configured to receive input lasers from the laser source 201 and generate signal states and decoy states by modifying laser intensity of the received input laser pulses. The phase modulator 212 is configured to implement random phase modulations of the signal states and the decoy states generated by the intensity modulator 211 to guarantee a phase randomization assumption. The polarization modulator 213 is configured to generate polarization states $|H\rangle$, $|V\rangle$, $|+\rangle$ and $|-\rangle$ based on the signal states and the decoy states modulated by the phase modulator 212.

[0048] In this embodiment, the polarization modulator 213 has the same structure as the third modulator 113 as shown in Figure 2B. The polarization modulator 213 includes an MZI modulator, a PPC, and two phase shifters disposed at two input arms of the PPC respectively. Light is coupled out of the transmitter chip, i.e., the silicon photonic chip of Alice 210a or Bob 210b, through an adiabatic tapered waveguide coupler and a lensed fibre, which may have a 3- μm spot diameter. The adiabatic tapered waveguide coupler may be designed with a cross-section of 200 nm $\times$ 220 nm to minimize the PDL. After attenuation, the weak coherent pulses from Alice 210a and Bob 210b reach the receiver, i.e. Charlie 220, via optical fibre spools 230a and 230b respectively.

[0049] The receiver, i.e., Charlie 220, includes a first EPC 223a and a second EPC 223b, a BS 221, a first PBS 222a and a second PBS 222b, and a first pair of single-photon

detectors (SPDs) 224a and a second pair of SPDs 224b, wherein the BS 221, and the two PBSs 222a and 222b are integrated onto a silicon photonic chip, i.e. the receiver chip. The first and second EPCs 221a and 221b are configured to receive the polarization states from Alice 210a and Bob 210b respectively and perform polarization drift compensation on the polarization states to maximize HOM interference between the polarization states. The BS 221 may be polarization-independent in this embodiment. The BS 221 and the two PBSs 222a and 222b are configured to perform Bell state measurement on the polarization states received from the two transmitters 110a and 110b. Specifically, the BS 221 is configured to perform two-photon interferometry/Hong-Ou-Mandel (HOM) interferometry; the two PBSs 222a and 222b are configured to measure horizontal and vertical polarization states, and the BS 221 and the two PBSs 222a and 222b jointly achieve the Bell state measurement for secret key generation. The two pairs of off-chip SPDs 224a and 224b are configured to detect photons from the two PBSs 223a and 223b respectively. Once the light is coupled out of the transmitter chips of Alice 210a and Bob 210b to the receiver 220, before entering the silicon photonic chip of the receiver 220, the pulses from Alice 210a and Bob 210b are compensated for polarization drift by the EPCs 223a and 223b respectively in order to maximize the HOM interference between the photons transmitted from Alice 210a and Bob 210b. Finally, Bell states are measured with the single-photon detectors 224a and 224b, and all coincidence events for secure key generation are publicly announced.

[0050] In this embodiment, both the transmitter and receiver chips may be fabricated by using advanced silicon photonic fabrication techniques, which utilize a silicon-on-insulator (SOI) wafer with a top silicon layer of approximately 220 nm and a buried oxide layer (BOX) of approximately 3 μm . The top silicon is etched to form a grating coupler. The slab layer of ridge waveguide in PPC and other components are fabricated using inductively coupled plasma-reactive ion etching (ICP-RIE). Subsequently, a strip waveguide is formed by etching through the remaining silicon. After finishing the waveguide etching, silicon oxide is deposited followed by titanium nitride (TiN) deposition to form the waveguide heaters. Then aluminum (Al) is deposited for electrical connection between an external power source and waveguide heaters. Finally, in order to prevent thermal crosstalk between adjacent heaters, isolation trenches are etched. The intensity modulator, phase modulator, and polarization modulator are integrated onto a single transmitter chip. Figures 5A and

5B illustrate optical micrographs of the transmitter chip and the receiver chip, as shown in Figure 4, respectively. Figure 5C shows the transmitter chip, as shown in Figure 4, packaged on a printed circuit board (PCB). In this embodiment, the receiver chip may be fabricated with adiabatic tapered waveguide couplers at input ports and grating couplers at output ports.

[0051] In this embodiment, the PPC is an important component of the transmitter chip. Further, as mentioned above, the two PBSs in the receiver chip may be replaced with PPCs. Therefore, the PPC may be also an important component of the receiver chip. As mentioned above, the PPC may include a polarization rotator and a mode combiner. Figures 6A-6D show the simulation and characterization results of the PPC according to the first embodiment of the invention. Figure 6A shows a plot illustrating a simulated transmission in a mode combiner of the PPC according to the first embodiment, with field propagations shown in insets of Figure 6A. Specifically, Figure 6A shows a mode conversion versus a coupling length L_c for TE_0 mode input at an upper port and a lower port of the mode combiner at a wavelength of $\lambda = 1.55 \mu\text{m}$. Figure 6A also shows spectrum diagrams illustrating field propagations in the mode combiner in two insets. As shown in Figure 6A, nearly 100% power conversion from TE_0 mode in the upper waveguide to TE_1 mode in the lower waveguide occurs at $L_c > 280 \mu\text{m}$, and the transmission of TE_0 mode at the lower port is unaffected. Figure 6B shows a plot illustrating a simulated transmission in the polarization rotator of the PPC according to the first embodiment, with field propagations shown in insets of Figure 6B. Specifically, Figure 6B shows a simulated transmission of TE_1 to TM_0 mode with respect to the length L_r of the polarization rotator of the PPC at $\lambda = 1.55 \mu\text{m}$. Figure 6B also shows spectrum diagrams illustrating field propagations in the polarization rotator in two insets. It is observed that the power is completely transferred from TE_1 mode to TM_0 mode as L_r increases to $80 \mu\text{m}$ and above, while the propagation of TE_0 mode remains unaffected. Therefore, L_r in the polarization rotator is set to $90 \mu\text{m}$ and L_c in the mode combiner is set to $300 \mu\text{m}$. In the transmitter chip, the PPC is used as a path to polarization converter, which combines $\alpha|TE_0\rangle$ of the upper waveguide and $\beta|TE_0\rangle$ of the lower waveguide with different amplitudes and relative phases into an arbitrary polarization state $\alpha|TM_0\rangle + \beta|TE_0\rangle$ that is then coupled to an optical fiber with the polarization of $\alpha|V\rangle + \beta|H\rangle$. α and β are parameters that contribute to the amplitude and

phase of light, and $|\alpha|^2 + |\beta|^2 = 1$. When the receiver chip includes two PPCs, each PPC may be employed inversely, and the arbitrary polarization of $\alpha|V\rangle + \beta|H\rangle$ from the optical fiber is converted into $\alpha|TE_0\rangle$ in the upper port of the mode combiner and $\beta|TE_0\rangle$ in the lower port of the mode combiner.

[0052] Figure 6C shows an optical micrograph of the mode combiner in the PPC, according to the first embodiment. Figure 6D shows a plot illustrating a measured transmission spectrum of the PPC for TE_0 input at the upper and lower ports of the mode combiner according to the first embodiment. The power is normalized to a straight waveguide below the PPC by subtracting the coupling loss between the optical fiber and the input/output waveguide. It is observed that the on-chip loss of TE_0 input is less than 0.3 dB at the lower port and less than 0.6 dB at the upper port of the mode combiner. The polarization extinction ratios (PERs) of the upper and lower output ports are greater than 22.5 dB and 20.5 dB, respectively, within the testing range between 1530 and 1570 nm. Referring to Figure 6D, in the chip-based MDI-QKD system according to one embodiment of the invention, when the wavelength of the laser source is set to 1542.3815 nm, a PER of approximately 26 dB is obtained for the lower port and a PER of approximately 32 dB is obtained for the upper port, as indicated by the line A in Figure 6D. Such a high PER would decrease the quantum bit error rate (QBER) which in turn improves the key rate in the MDI-QKD system.

[0053] In this embodiment, the transmitter chips may be calibrated using a fiber-based polarization alignment system that includes a 50:50 BS for passive selection of the measurement basis. The 50:50 BS may include a first arm coupled to a first PBS/PPC of the receiver chip to measure $|H\rangle$ and $|V\rangle$, and a second arm coupled to a second PBS/PPC of the receiver chip to measure $|+\rangle$ and $|-\rangle$.

Experimental setup and results

[0054] In one experiment according to some embodiments of the invention, each of the two transmitters Alice and Bob includes an independent frequency-locked laser source, e.g., Clarity-NLL-1542-HP, with LiNbO3 intensity modulator, producing 10-ns laser pulses at 1542.3815 nm with a repetition rate of 0.5 MHz. This configuration allows the

transmitter chips to prepare weak coherent states in one of four polarization states: $|H\rangle$, $|V\rangle$, $|+\rangle$ and $|-\rangle$, wherein $|H\rangle$ and $|V\rangle$ may be rectilinear or Z basis, and $|+\rangle$ and $|-\rangle$ may be diagonal or X basis. Alice, Bob, and Charlie share an electrically distributed reference clock to which their preparation and detection equipment are synchronized. Free-running

5 InGaAs/InP avalanche photodiodes ID230 are synchronized and gated to the arrival time of the photons with a 50- μ s deadtime. The coincidence window of the single-photon detectors is set to around 22 ns. The efficiency of the single-photon detectors is kept at around 25% for all the data points in the experiment.

[0055] In this experiment, the two transmitter chips are calibrated using a fibre-based polarization alignment system. By tuning the voltages applied to the MZI modulator and one of the phase shifters in the polarization modulator, polarization states in rectilinear (Z) and diagonal (X) bases are obtained with PERs over 20 dB. Figure 7 shows a plot illustrating the on-chip polarization state preparation in this experiment. Specifically, Figure 7 shows a normalized transmission of four polarization states versus voltages applied to the MZI modulator in the polarization modulator. In Figure 7, the normalized transmission of the four polarization states $|H\rangle$, $|V\rangle$, $|+\rangle$ and $|-\rangle$ are shown in triangles, circles, diamonds, and squares respectively. The voltages on each phase shifter of the polarization modulator are respectively fixed to 1.50, 2.65, 1.80 and 2.22 V for $|H\rangle$, $|V\rangle$, $|+\rangle$ and $|-\rangle$ states during the measurement. The lines connecting the triangles, circles, diamonds, and squares respectively represent the fitted curves for $|H\rangle$, $|V\rangle$, $|+\rangle$ and $|-\rangle$ states, respectively. The polarization modulator is capable of providing an extinction ratio of over 20 dB. For the intensity modulator, a typical extinction ratio of 30 dB is achieved, which is sufficient for a decoy-state MDI-QKD system.

[0056] A four-intensity decoy-state MDI-QKD protocol is demonstrated on the chip-based MDI-QKD system proposed by embodiments of the invention as a proof of concept. Each time the transmitter chips randomly and independently choose one of the four intensities, $\{\mu, \nu, \omega, 0\}$ ($\nu > \omega$), with probabilities of p_μ , p_ν , p_ω , and p_0 , respectively, to send weak coherent states to the receiver. The states with the intensity μ are prepared in Z basis and those with the intensities ν and ω are prepared in X basis. The states with the intensity 0 are vacuum states. With the finite-key effect taken into consideration, the key rate of the

30 protocol is given by the following Equation:

$$R = p_{\mu}^2 \left\{ \mu e^{-\mu} \underline{s}_{11} \left[1 - H(\overline{e}_{11}^{ph}) \right] - f S_{\mu\mu} H(E_{\mu\mu}) \right\} - \frac{1}{N_{total}} \left(\log_2 \frac{2}{\varepsilon_{cor}} + 2 \log_2 \frac{2}{\sqrt{2} \hat{\varepsilon} \varepsilon_{PA}} \right)$$

where $\underline{s}_{11}$ and $\overline{e}_{11}^{ph}$ are the bound of counting rate and a phase-flip error rate of single-photon pulse pairs that can be obtained by the decoy-state method, $S_{\mu\mu}$ and $E_{\mu\mu}$ are counting rate and bit-flip error rate when Alice and Bob both send states with the intensity μ , $H(p) = -p \log_2 p - (1-p) \log_2 (1-p)$ is the binary entropy function, f is the correction efficiency, which is set to 1.1, N_{total} is the total number of pulses that each of Alice and Bob sends, and ε_{cor} , ε_{PA} , and $\hat{\varepsilon}$ are some failure probabilities in the finite-key analysis, all of which are set to 10^{-10} in the calculation. The four-intensity protocol uses the joint constraints in a statistical fluctuation of different observables, which greatly improves the key rate.

[0057] Since MDI-QKD primarily relies on HOM interference at the receiver, the transmitters are required to produce indistinguishable states to maximize the interference. To achieve this goal, the wavelength, time, intensity, and polarization degrees of freedom of the input weak coherent pulses are carefully adjusted in this experiment. A HOM visibility of approximately 48% is achieved, which is comparable to the theoretical maximal visibility of 50% with weak coherent states. The four-intensity decoy-state protocol is implemented with intensities of $\{\mu = 0.374, \nu = 0.228, \omega = 0.071, o = 0\}$ and the finite-key effect taken into consideration. The parameters are optimized using the joint constraints in statistical fluctuation of different observables.

[0058] Figure 8 shows a plot illustrating a comparison of theoretical and experimental results of the secure key rate per pulse versus different transmission distances with various types of single-photon detectors according to some embodiments of the invention. In Figure 8, the solid line represents the theoretical simulation result according to the corresponding experimental conditions using InGaAs/InP single-photon avalanche diodes with a detection efficiency of approximately 25%. The solid triangle shows the experimental result with a total transmission loss of 10 dB, which corresponds to fibre distance of 50 km. The dash line and dash-dot line show the simulation results with two different superconducting nanowire single-photon detectors SNSPD1 and SNSPD2. SNSPD1 has a detection efficiency of 53%, and SNSPD2 has a detection efficiency of 85%. Key rate per pulse of four previous MDI-QKD experiments in Ref.1, Ref. 2, Ref. 3,

and Ref. 4 are also plotted in Figure 8 as hollow square, hollow circle, hollow diamond, and hollow star, respectively. The data in this experiment are collected by using optical attenuators to emulate the attenuation of standard single-mode fibre in 0.2 dB/km. Due to the optimal interference, a QBER of approximately 0.67% is observed in the Z basis. QBER measured in the X basis is approximately 25.6%, which is comparable to the theoretical value of 25% on account of the visibility limit of 50%. At a total loss of 10 dB, which corresponds to a distance of 50 km in a standard fibre, 4.0×10^{10} pulse pairs are sent from each transmitter chip. The key rate per pulse is 2.923×10^{-6} , which matches well with the theoretical simulation and is comparable to the results from previous MDI-QKD studies, as shown in Figure 8. Considering the clock rate of 0.5 MHz in the experiment, a secret key rate of 1.46 bps with a distance corresponding to 50 km has been achieved. By evaluating the parameters of a detector with a higher detection efficiency of 85%, the same MDI-QKD chips are capable of transmitting keys over 120 km, as shown in Figure 8.

[0059] In conclusion, various embodiments of the invention, for the first time, provide an all-on-chip photonic MDI-QKD system based on silicon photonic chips. The system includes two chip-based transmitters and a chip-based receiver. The transmitter includes a transmitter chip with integrated intensity modulator, phase modulator, and polarization modulators. The receiver includes a receiver chip with integrated BS and two PBSs/PPCs. These integrated chips are capable of generating polarization-encoded weak coherent states with PERs over 20 dB, which meet the requirements for low-error MDI-QKD. The transmitter chips have been used in the proof-of-concept experiment to implement the BB84 MDI-QKD protocol over a distance corresponding to 50 km with 25% detection efficiency, and a predicted distance over 120 km with 85% detection efficiency. The key rate per pulse of 2.923×10^{-6} is comparable to that reported in previous works and can be further optimized by using single-photon detectors with higher detection efficiency. The proposed chip-based MDI-QKD system is cost-effective and power-efficient and can be readily incorporated into existing optical fiber communication networks, thereby promising great potential towards highly integrated quantum communication networks for quantum internet and quantum-classical hybrid communication. With further integration of optical switches, wavelength demultiplexers, and multi-channel single-photon detectors

on the receiver chip, it is possible to build a fully chip-based MDI-QKD server in the near future.

[0060] It is to be understood that the embodiments and features described above should be considered exemplary and not restrictive. various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments of the invention.

Reference

[0061] Ref.1: Tang, Z., Wei, K., Bedroya, O., Qian, L. & Lo, H.-K. Experimental measurement-device-independent quantum key distribution with imperfect sources. Phys. Rev. A 93, 042308 (2016).

[0062] Ref.2: Tang, Y.-L. et al. Measurement-device-independent quantum key distribution over 200 km. Phys. Rev. Lett. 113, 190501 (2014).

[0063] Ref.3: Rubenok, A., Slater, J.A., Chan, P., Lucio-Martinez, I. & Tittel, W. Real-world two-photon interference and proof-of-principle quantum key distribution immune to detector attacks. Phys. Rev. Lett. 111, 130501 (2013).

[0064] Ref.4: Da Silva, T.F. et al. Proof-of-principle demonstration of measurement-device-independent quantum key distribution using polarization qubits. Phys. Rev. A 88, 052303 (2013).

CLAIMS

1. A system for measurement-device-independent (MDI) quantum key distribution (QKD), the system comprising two transmitters and a receiver, wherein each of the two transmitters is communicably connectable to the receiver and comprises a first modulator, a second modulator, and a third modulator which are integrated onto a silicon photonic chip, wherein:

the first modulator is configured to receive input laser pulses from a laser source and generate signal states and decoy states by modifying laser intensity of the received input laser pulses;

the second modulator is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator; and

the third modulator is configured to generate polarization states based on the signal states and the decoy states modulated by the second modulator.

2. The system according to claim 1, wherein the third modulator comprises:

a Mach-Zehnder interferometer (MZI) modulator configured to generate a first transverse electric (TE) mode of a first waveguide and a second TE mode of a second waveguide based on the signal states and decoy states modulated by the second modulator and adjust an intensity difference between the first TE mode and the second TE mode;

two phase shifters configured to receive the first TE mode and the second TE mode respectively and adjust a phase difference between the first TE mode and the second TE mode; and

a path-to-polarization converter (PPC) configured to generate a polarization state based on the first TE mode and the second TE mode.

3. The system according to claim 2, wherein each transmitter further comprises:

an adiabatic tapered waveguide coupler integrated onto the silicon photonic chip and configured to couple the generated polarization state to the receiver.

4. The system according to claim 3, wherein the adiabatic tapered waveguide coupler has a rectangular cross-sectional shape of approximately 200nm by 220nm at one end of the adiabatic tapered waveguide coupler to minimize the polarization-dependent loss (PDL).

5

5. The system according to any one of claim 2 to claim 4, wherein the PPC comprises a polarization rotator configured to convert one of the first TE mode and the second TE mode into a transverse magnetic (TM) mode, and a mode combiner configured to combine the TM mode and the first TE mode or the second TE mode which is not converted to generate the polarization state.

10

6. The system according to claim 1, wherein the third modulator comprises:

a Mach-Zehnder interferometer (MZI) modulator configured to generate a first transverse electric (TE) mode of a first waveguide and a second TE mode of a second waveguide based on the signal states and decoy states modulated by the second modulator and adjust an intensity difference between the first TE mode and the second TE mode;

15

two phase shifters configured to receive the first TE mode and the second TE mode respectively and adjust a phase difference between the first TE mode and the second TE mode; and

20

a two-dimensional (2D) grating coupler configured to generate a polarization state based on the first TE mode and the second TE mode and couple the generated polarization state to a receiver.

7. The system according to any preceding claim, wherein the laser source comprises a pulse-modulated frequency-locked laser which is coupled to a silicon waveguide of the transmitter through a grating coupler.

25

8. The system according to any one of claim 1 to claim 7, wherein the receiver comprises a beam splitter (BS), a first polarizing beam splitter (PBS), and a second PBS, wherein the BS and the first and the second PBSs are integrated onto a silicon photonic

30

chip to perform Bell state measurement on the polarization states received from the two transmitters.

9. The system according to any one of claim 1 to claim 7, wherein the receiver
5 comprises a beam splitter (BS), a first path-to-polarization converter (PPC), and a second
PPC, wherein the BS and the first and the second PPCs are integrated onto a silicon
photonic chip to perform Bell state measurement on the polarization states received from
the two transmitters.

10 10. The system according to any preceding claim, wherein each of the two transmitters
is communicably connected to the receiver through a lensed fiber or a standard single-mode
fiber.

11. The system according to any one of claim 9 to claim 10, wherein the receiver further
15 comprises two electrical polarization controllers (EPCs) configured to receive the
polarization states from the two transmitters respectively and perform polarization drift
compensation on the polarization states to maximize Hong-Our-Mandel (HOM)
interference between the polarization states.

20 12. The system according to any one of claim 9 to claim 11, wherein the receiver further
comprises a first pair of single-photon detectors (SPDs) and a second pair of SPDs, wherein
the first pair of SPDs is configured to detect photons from the first PBS or the first PPC,
and the second pair of SPDs is configured to detect photons from the second PBS or the
second PPC.

25 13. The system according to any preceding claim, wherein the two transmitters and/or
the receiver are fabricated on a silicon-on-insulator wafer.

14. The system according to any one of claim 1 to claim 13, further comprising a fiber-
30 based polarization alignment system configured to calibrate the two transmitters.

15. A transmitter for measurement-device-independent (MDI) quantum key distribution (QKD), the transmitter comprising a first modulator, a second modulator, and a third modulator which are integrated onto a silicon photonic chip, wherein:

the first modulator is configured to receive input laser pulses from a laser source
5 and generate signal states and decoy states by modifying laser intensity of the received input laser pulses;

the second modulator is configured to implement random phase modulations of the signal states and the decoy states generated by the first modulator; and

the third modulator is configured to generate polarization states based on the signal
10 states and decoy states modulated by the second modulator.

16. The transmitter according to claim 15, wherein the third modulator comprises:

a Mach-Zehnder interferometer (MZI) modulator configured to generate a first
transverse electric (TE) mode of a first waveguide and a second TE mode of a second
15 waveguide based on the signal states and decoy states modulated by the second modulator and adjust an intensity difference between the first TE mode and the second TE mode;

two phase shifters configured to receive the first TE mode and the second TE mode
respectively and adjust a phase difference between the first TE mode and the second TE
mode; and

20 a path-to-polarization converter (PPC) configured to generate a polarization state based on the first TE mode and the second TE mode.

17. The transmitter according to claim 16, wherein each transmitter further comprises:
an adiabatic tapered waveguide coupler integrated onto the silicon photonic chip and
25 configured to couple the generated polarization state to a receiver.

18. The transmitter according to claim 17, wherein the adiabatic tapered waveguide
coupler has a rectangular cross-sectional shape of approximately 200nm by 220nm at one
end of the adiabatic tapered waveguide coupler to minimize the polarization-dependent
30 loss (PDL).

19. The transmitter according to any one of claim 16 to claim 18, wherein the PPC comprises a polarization rotator configured to convert one of the first TE mode and the second TE mode into a transverse magnetic (TM) mode, and a mode combiner configured to combine the TM mode and the first TE mode or the second TE mode which is not converted to generate the polarization state.

20. The transmitter according to claim 15, wherein the third modulator comprises:
a Mach-Zehnder interferometer (MZI) modulator configured to generate a first transverse electric (TE) mode of a first waveguide and a second TE mode of a second waveguide based on the signal states and decoy states modulated by the second modulator and adjust an intensity difference between the first TE mode and the second TE mode;
two phase shifters configured to receive the first TE mode and the second TE mode respectively and adjust a phase difference between the first TE mode and the second TE mode; and
a two-dimensional (2D) grating coupler configured to generate a polarization state based on the first TE mode and the second TE mode and couple the generated polarization state to a receiver.

21. The transmitter according to any one of claim 15 to claim 20, wherein the transmitter is fabricated on a silicon-on-insulator wafer.

22. A receiver for measurement-device-independent (MDI) quantum key distribution (QKD), the receiver comprising a beam splitter (BS), a first polarizing beam splitter (PBS), and a second PBS, wherein the BS and the first and the second PBSs are integrated onto a silicon photonic chip to perform Bell state measurement on polarization states received from two transmitters, wherein each transmitter is fabricated according to any one of claim 15 to claim 21.

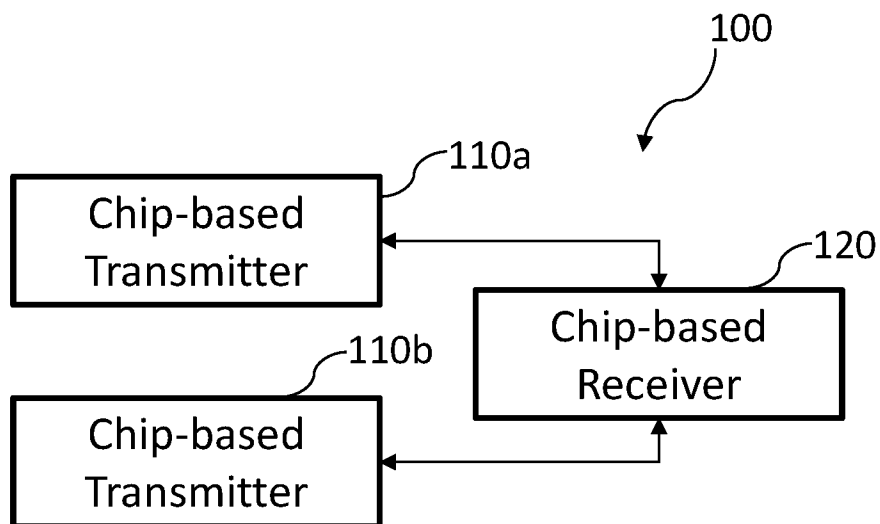
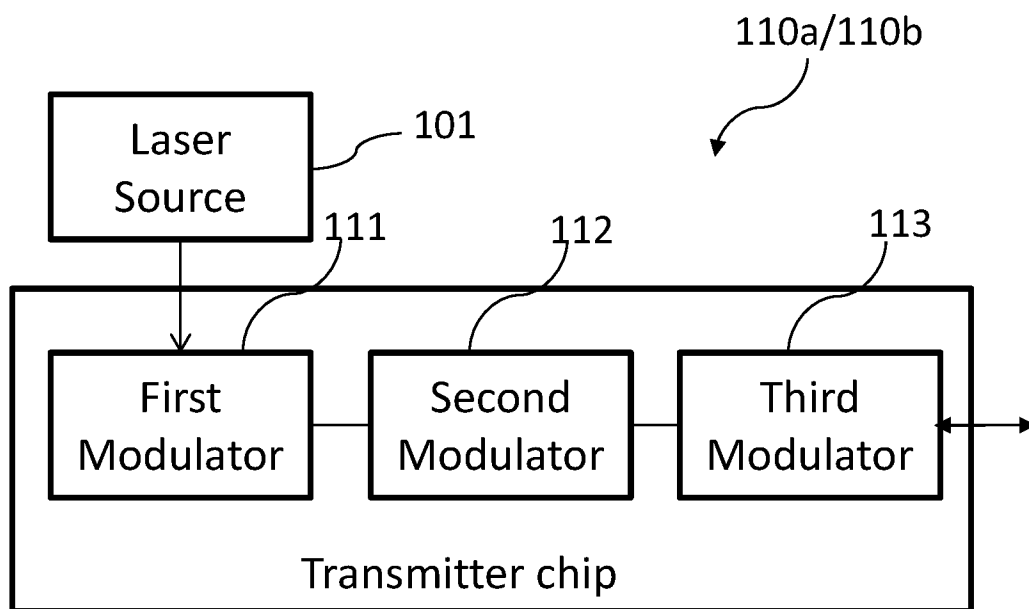
23. A receiver for measurement-device-independent (MDI) quantum key distribution (QKD), the receiver comprising a beam splitter (BS), a first path-to-polarization converter (PPC), and a second PPC, wherein the BS and the first and the second PPCs are integrated

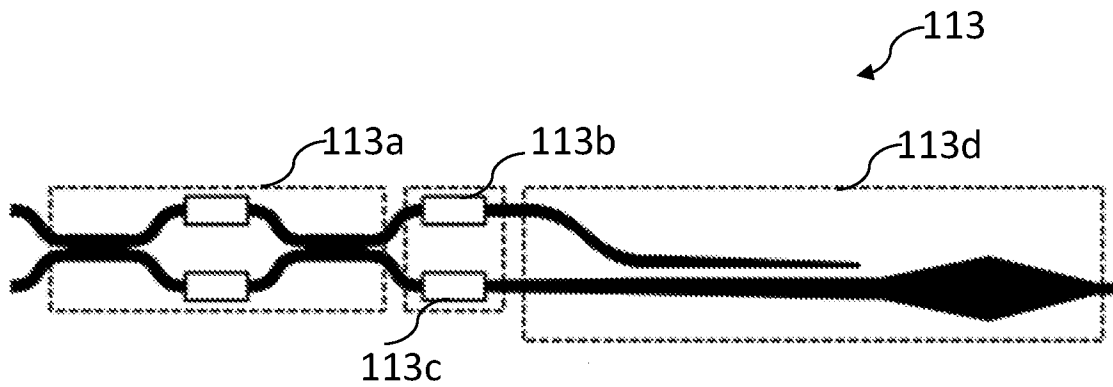
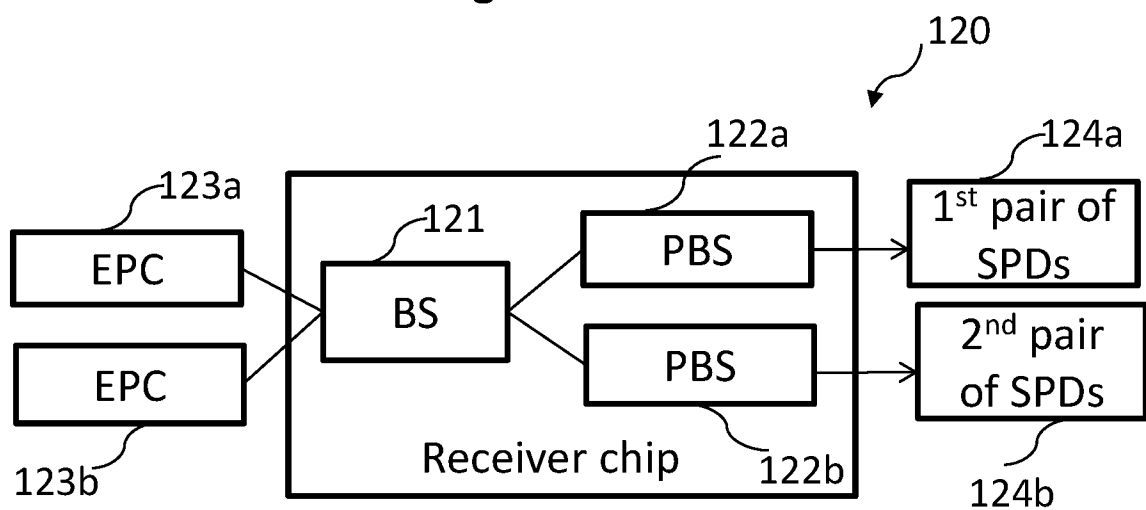
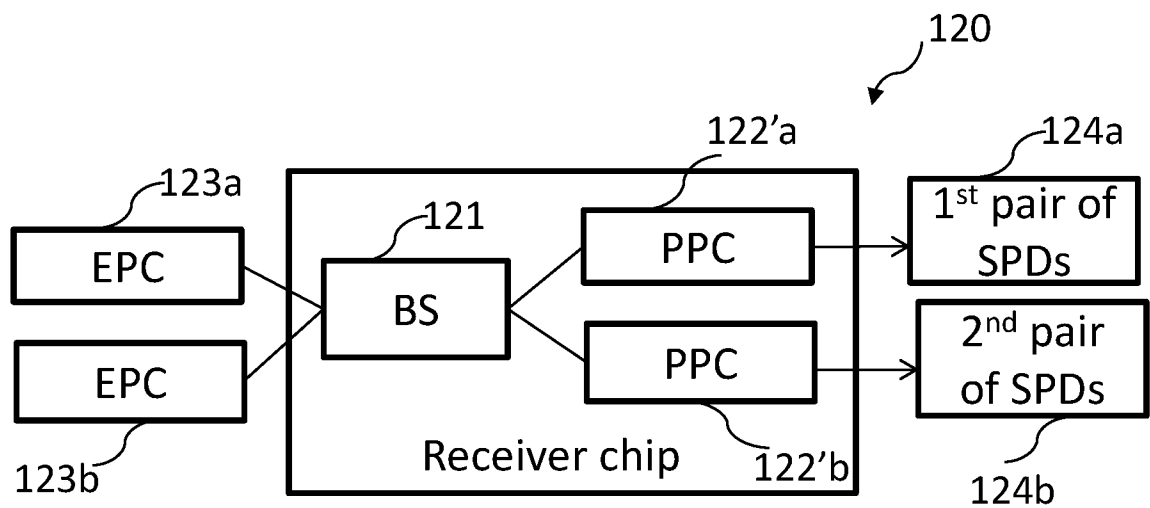
onto a silicon photonic chip to perform Bell state measurement on the polarization states received from two transmitters wherein each transmitter is fabricated according to any one of claim 15 to claim 21.

5 24. The receiver according to claim 22 or claim 23, wherein the receiver further comprises two electrical polarization controllers (EPCs) configured to receive polarization states from the two transmitters respectively, and perform polarization drift compensation on the polarization states to maximize Hong-Our-Mandel (HOM) interference between the polarization states.

10

25. The receiver according to any one of claim 22 to claim 24, further comprising a first pair of single-photon detectors (SPDs) and a second pair of SPDs, wherein the first pair of SPDs is configured to detect photons from the first PBS or the first PPC, and the second pair of SPDs is configured to detect photons from the second PBS or the second
15 PPC.

**Figure 1****Figure 2A**

**Figure 2B****Figure 3A****Figure 3B**

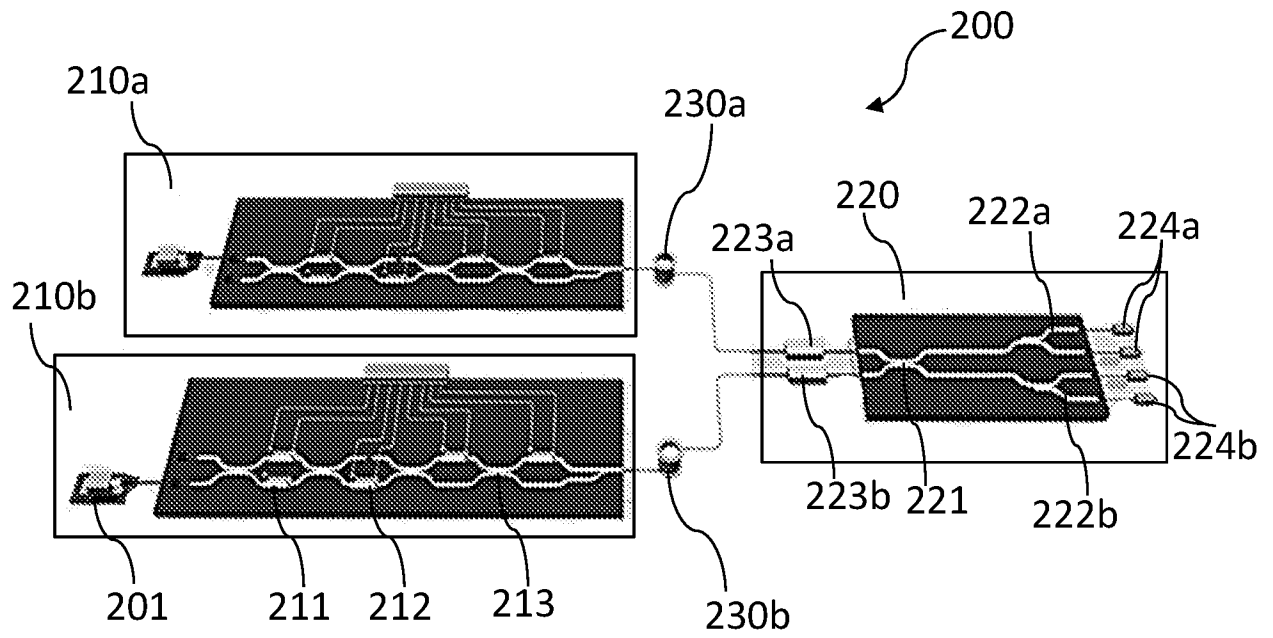


Figure 4

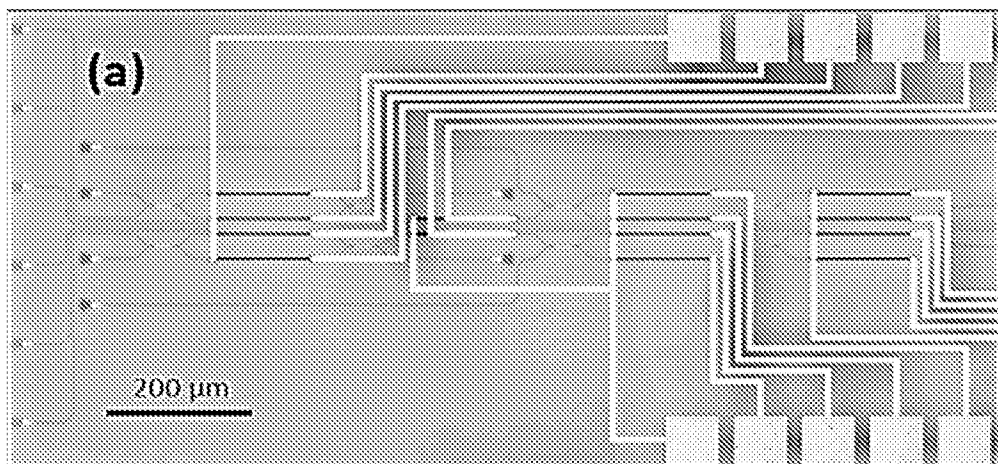


Figure 5A

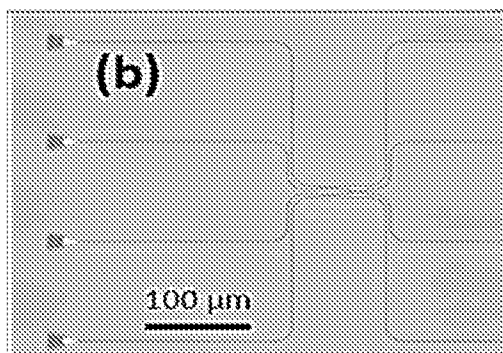


Figure 5B

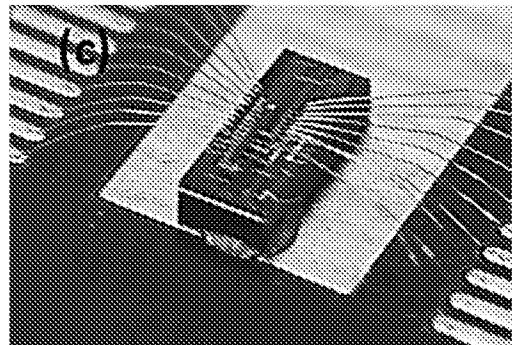


Figure 5C

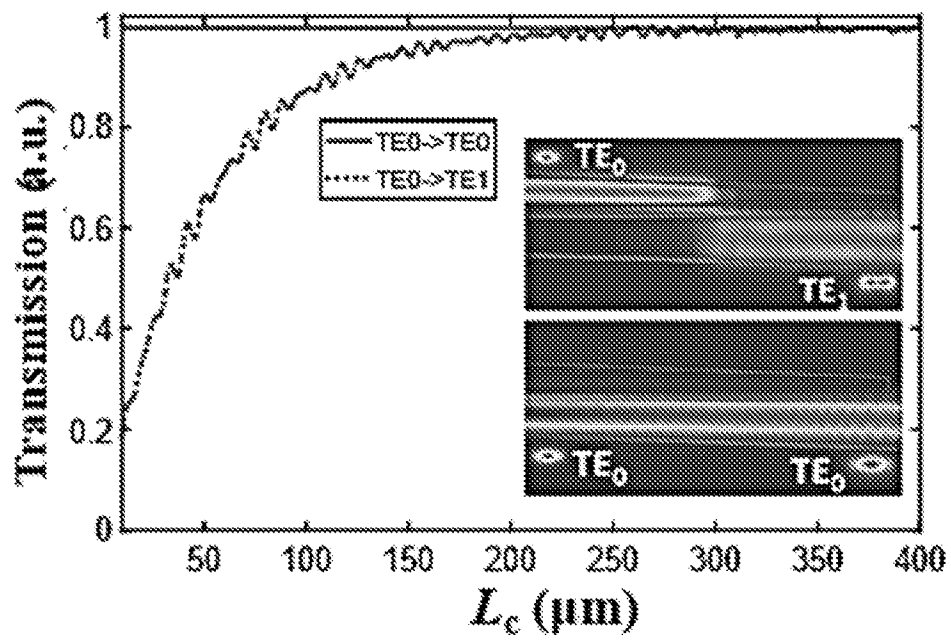


Figure 6A

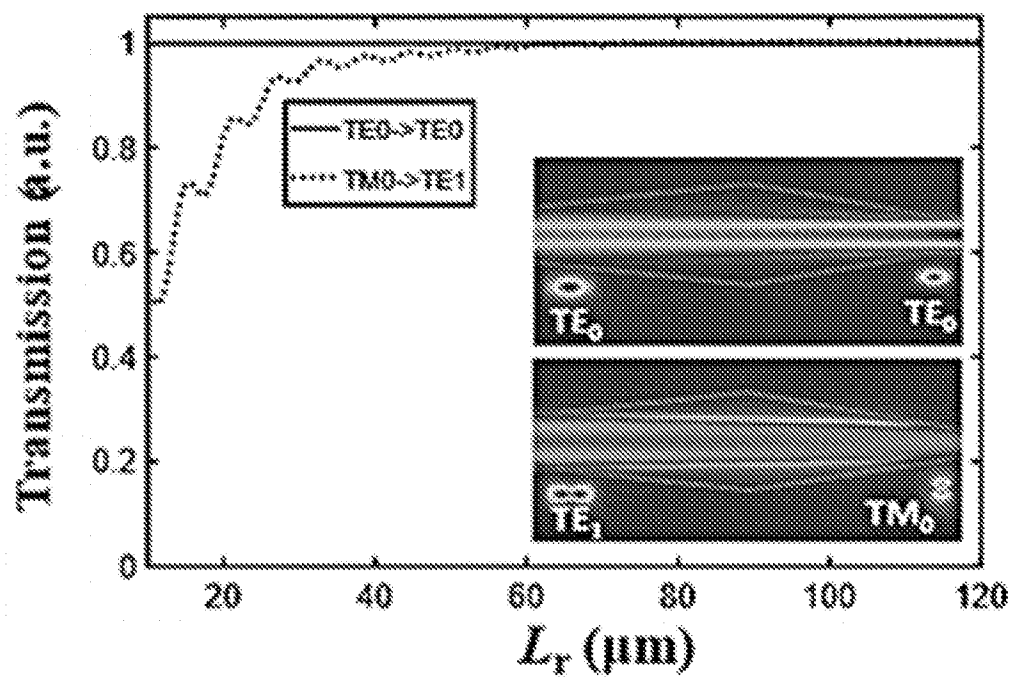


Figure 6B

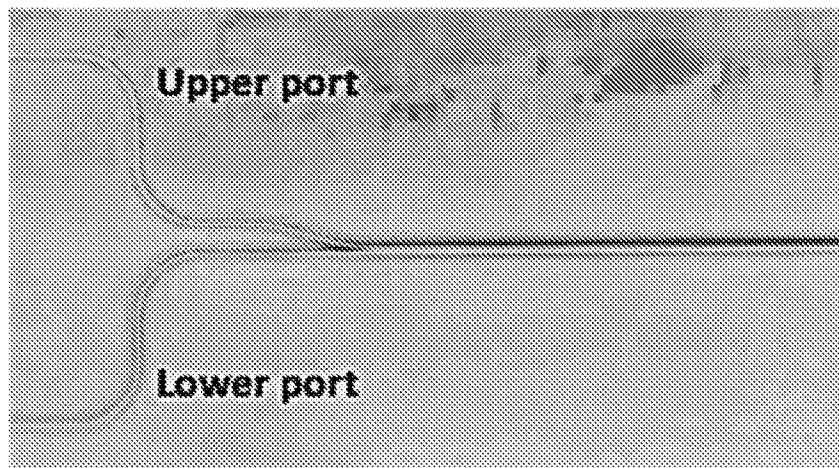


Figure 6C

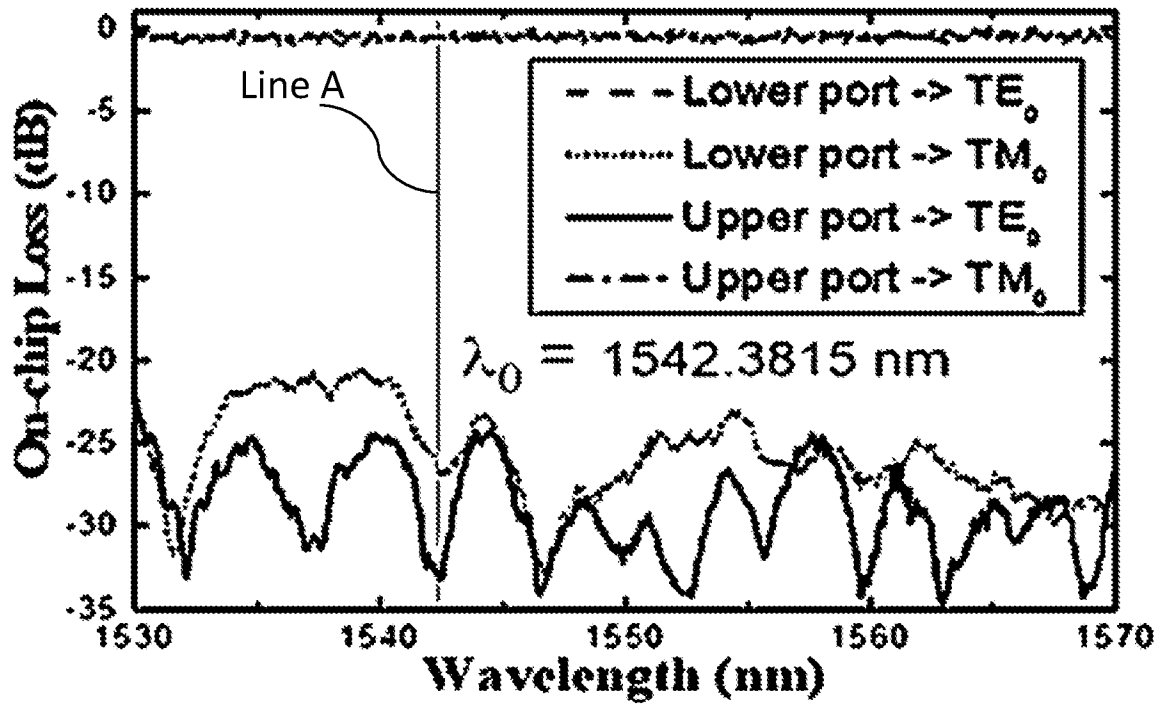


Figure 6D

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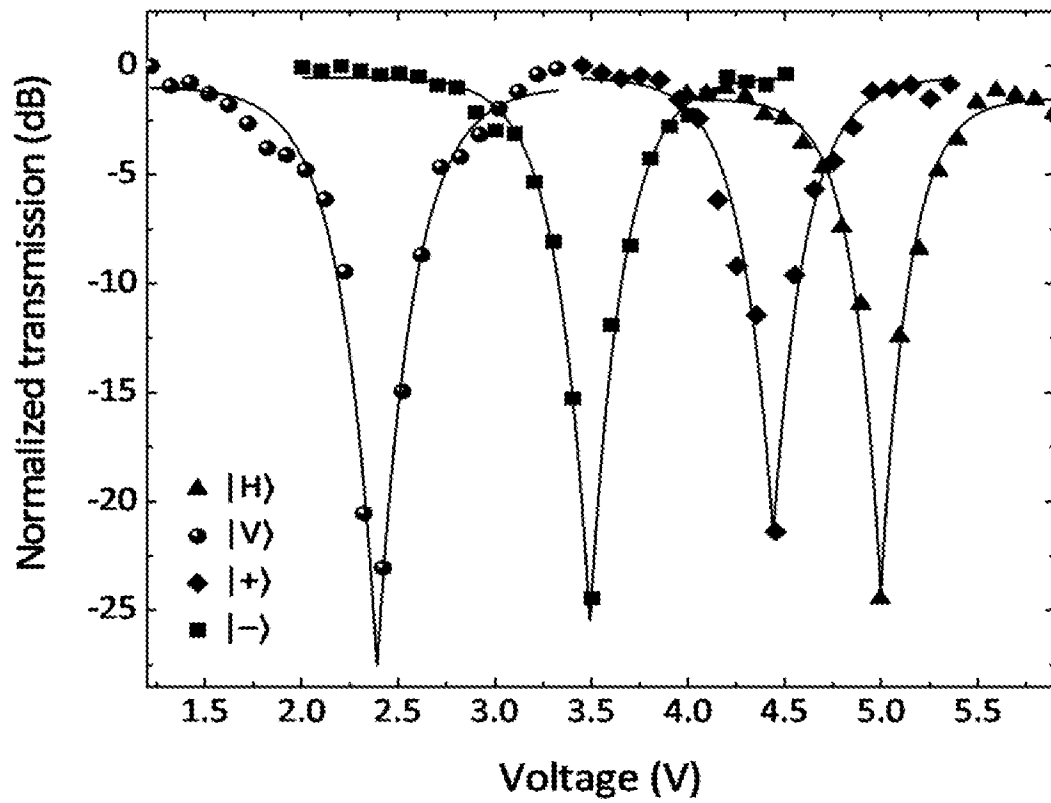


Figure 7

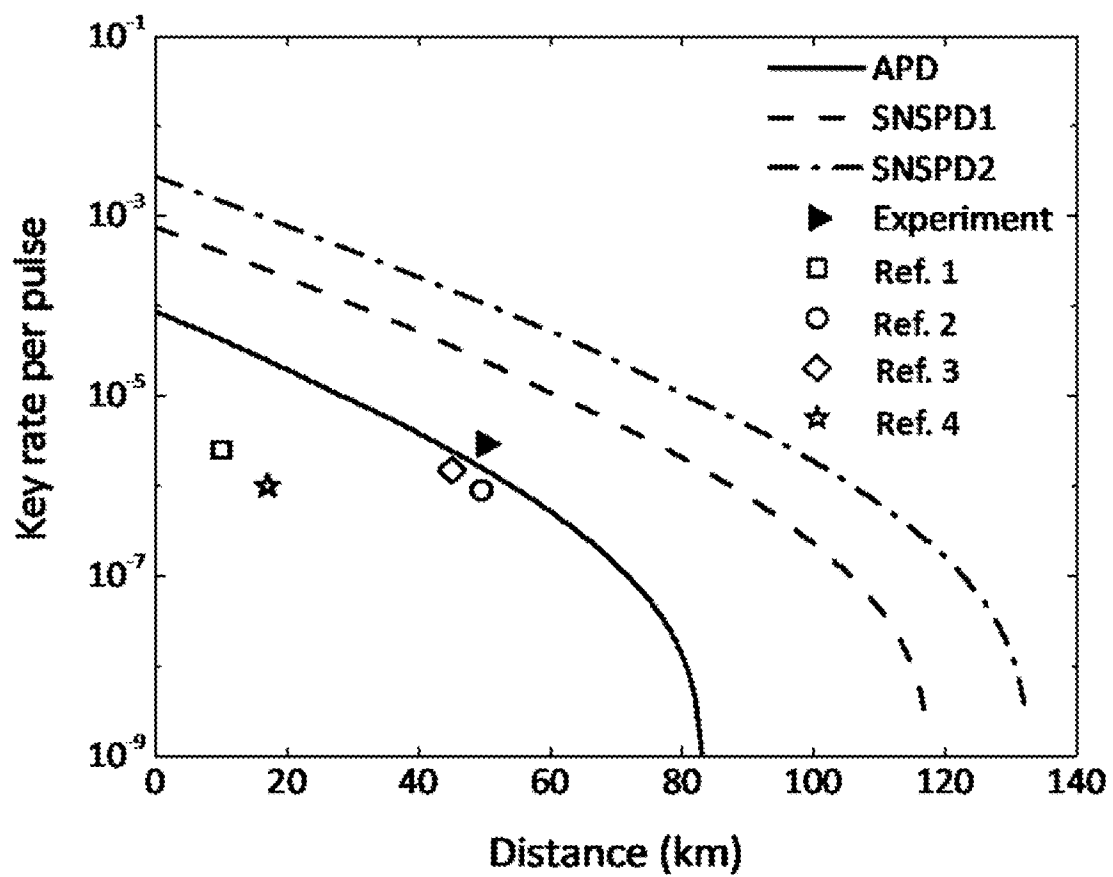


Figure 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2021/050098

A. CLASSIFICATION OF SUBJECT MATTER

H04B 10/516 (2013.01) H04B 10/70 (2013.01) H04L 9/08 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04B; H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT, IEEE, CNKI: measurement device independent, quantum key distribution, QKD, first, second, third, modulator, laser, source, light, intensity, random, phase, angle, polarization, state, 测量设备无关,量子密钥分发,第一,第二,第三,调制器,激光,光源,光,强度,随机,角度,相位,偏振 and other related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2018/0241553 A1 (LUCAMARINI M. ET AL.) 23 August 2018 Figs. 1-2, 4; Paras. [0031], [0045]-[0049], [0057]-[0071], [0147], [0182]	1-25
X	CN 110601839 A (SONG X. ET AL.) 20 December 2019 Paras. [0015], [0023]-[0025] of the original non-English language document (a machine translation is enclosed only for your reference)	1-25
A	CN 110880970 A (XI'AN UNIVERSITY OF POST & TELECOMMUNICATIONS) 13 March 2020 The whole document, especially Fig. 2 of the original non-English language document (a machine translation is enclosed only for your reference)	

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

11/05/2021

(day/month/year)

Date of mailing of the international search report

14/05/2021

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2021/050098

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 207968508 U (GUANGDONG NATIONAL QUANTUM TECHNOLOGY) 12 October 2018 The whole document of the original non-English language document (a machine translation is enclosed only for your reference)	
A	CN 209313852 U (UNIVERSITY OF SCIENCE & TECHNOLOGY OF CHINA) 27 August 2019 The whole document of the original non-English language document (a machine translation is enclosed only for your reference)	
A	CN 210112021 U (SONG X. ET AL.) 21 February 2020 The whole document of the original non-English language document (a machine translation is enclosed only for your reference)	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2021/050098

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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CN 110601839 A	20/12/2019	NONE	
CN 110880970 A	13/03/2020	NONE	
CN 207968508 U	12/10/2018	NONE	
CN 209313852 U	27/08/2019	NONE	
CN 210112021 U	21/02/2020	NONE	