indistinguishable single photons in large numbers and at a suitably high emission rate. Further, the ability to operate these single photon sources without requiring cryogenic cooling, and the ability to manufacture such sources at scale to a consistent quality and performance, would facilitate their adoption and enable the development of quantum computing and information processing technologies.

[0005] Single photons can also emitted by quantum objects, such as trapped ions and neutral atoms, which may be used as physical qubits, for example in a quantum computer. In this case, the physical qubit acts as a single photon generating material. Transitions that emit single photons from these quantum objects can provide a mechanism for interfacing with the physical qubits to manipulate or interrogate them. However, these transitions to generate single photons do not reliably occur at a sufficiently high rate.

[0006] The present disclosure has been devised in the foregoing context.

Summary

[0006a] In an aspect, the present disclosure refers to an apparatus for providing a light-matter interface for enhancing transitions that generate single photons, the apparatus comprising:

a first reflective surface;

a locking recess formed in a locking reflective surface, the first reflective surface and locking recess forming a locking cavity to receive light from a locking laser, the portion of light output from the locking cavity indicative of whether the locking cavity is on resonance with the locking laser;

an emitting recess formed in an emitting reflective surface, the first reflective surface and emitting recess forming an emitting cavity to receive photons from a single photon emitter material,

the single photon emitter material located in the emitting cavity to emit single photons in response to optical or electrical excitation of the material; and

an actuator to tune the length of the locking cavity based on the portion of light output from the locking cavity to be on resonance with the locking laser to lock the locking cavity to the locking laser,

wherein the locking reflective surface and emitting reflective surface are mechanically coupled such that locking the locking cavity tunes and stabilises the emitting cavity at a single photon emission wavelength.

[0006b] In an aspect, the present disclosure refers to a system for providing a light-matter interface for enhancing transitions that generate single photons, the system comprising:

an apparatus according to the above aspect; and

optics for transmitting light into the locking cavity of the apparatus.

[0006c] In an aspect, the present disclosure refers to a method of manufacturing an apparatus for providing a light-matter interface for enhancing transitions that generate single photons, the method comprising:

providing a locking substrate comprising a locking reflective surface;

forming a recess in the locking reflective surface to form a locking cavity with a first reflective surface of a first substrate;

providing an emitting substrate comprising an emitting reflective surface, the emitting substrate and locking substrate being mechanically coupled;

forming a recess in the emitting reflective surface to form an emitting cavity with the first reflective surface of the first substrate;

providing a single photon emitter material for emitting single photons located in the emitting cavity;

providing the first substrate comprising the first reflective surface; and

tuning the length of the locking cavity based on the cavity length of the locking cavity to tune the length of the emitting cavity into a fixed configuration, to be fine tuned by an actuator during use.

[0006d] In an aspect, the present disclosure refers to a method for generating single photons, the method comprising:

receiving light at a locking cavity from a locking laser, the locking cavity formed from a first reflective surface and a locking recess formed in a locking reflective surface, the portion of light output from the locking cavity indicative of whether the locking cavity is on resonance with the locking laser;

tuning the length of the locking cavity based on the portion of light output from the locking cavity to be on resonance with the locking laser to lock the locking cavity to the locking laser; and

emitting, by single photon emitter material located in an emitting cavity, single photons in response to optical or electrical excitation of the material, the emitting cavity formed from the first reflective surface and an emitting recess formed in an emitting reflective surface;

wherein the locking reflective surface and emitting reflective surface are mechanically coupled such that locking the locking cavity tunes and stabilises the emitting cavity at a single photon emission wavelength.

[0007] Viewed from one example, the present disclosure provides an apparatus for generating single photons. In particular, the apparatus may be considered to provide a light-matter interface for enhancing transitions that generate single photons. The apparatus comprises: a first reflective surface; a locking recess formed in a locking reflective surface, the first reflective surface and locking recess forming a locking cavity to receive light from a locking laser, the portion of light output from the locking cavity indicative of whether the locking cavity is on resonance with the locking laser; an emitting recess formed in an emitting reflective surface, the first reflective surface and emitting recess forming an emitting cavity to receive photons from a single photon emitter material, the single photon emitter material located in the emitting cavity to emit single photons in response to optical or electrical excitation of the material; and an actuator to tune the length of the locking cavity based on the portion of light output from the locking cavity to be on resonance with the locking laser to lock the locking cavity to the locking laser, wherein the locking reflective surface and emitting reflective surface are mechanically coupled such that locking the locking cavity tunes and stabilises the emitting cavity at a single photon emission wavelength.

[0008] Viewed from another example, the present disclosure provides a method for generating single photons. In particular, the method may be considered to provide a light-matter interface for enhancing transitions that generate single photons. The method comprises: receiving light at a locking cavity from a locking laser, the locking cavity formed from a first reflective surface and a locking recess formed in a locking reflective surface, the portion of light output from the

locking cavity indicative of whether the locking cavity is on resonance with the locking laser; tuning the length of the locking cavity based on the portion of light output from the locking cavity to be on resonance with the locking laser to lock the locking cavity to the locking laser; and emitting, by single photon emitter material located in an emitting cavity, single photons in response to optical or electrical excitation of the material, the emitting cavity formed from the first reflective surface and an emitting recess formed in an emitting reflective surface; wherein the locking reflective surface and emitting reflective surface are mechanically coupled such that locking the locking cavity tunes and stabilises the emitting cavity at a single photon emission wavelength.

[0009] In accordance with the above examples of the disclosure, a single photon emitting material is provided coupled in an optically resonant cavity to enhance emission and raise the photon generation efficiency thereof, wherein a separate mechanically coupled locking cavity is provided that can be used, in conjunction with an appropriate stable laser, to control the actuator to maintain the locking cavity on resonance with the stable laser, using an appropriate locking technique. By maintaining the locking cavity optically tuned to a stable laser, the mechanically coupled emitting cavity containing the single photon emitting material can also be maintained in a stable tuning, which may be configured to be resonant with an emission wavelength of the single photon emitting material, such as a zero phonon line thereof, allowing suppression of a phonon side-band thereof. In this way, apparatuses in accordance with the above example of the disclosure, can be controlled to maintain long term emission cavity mode stability at the single photon emission wavelength. Moreover, as the single photon emitting material can be maintained in a stable tuning using the locking cavity mechanically coupled to the emitting cavity, the apparatus does not require a specific single photon emitting material because the locking cavity, and consequently the tuning, can be adjusted based on the material. Further, as the tuning of the locking cavity tunes the emission cavity through a mechanical coupling in the apparatus, the locking cavity can be tuned using light that is separate from the emission cavity, meaning that the light from the locking laser is decoupled from the photons from the single photon emitter. That is, the light from the locking laser can be used to tune the emitting cavity used to enhance the emission of single photons from the material, without it entering the emitting cavity, or needing to be separated from the emitted single photons. Thus the apparatus can be used to reliably generate a stable source of indistinguishable photons from a suitable single photon emitting material.

[0010] In examples, the portion of light output from the locking cavity may be the portion of light reflected and/or transmitted from the locking cavity. The mode locking of the cavity

may be conducted using the portion of light reflected from the cavity or the portion of light transmitted through the cavity, although performance may be better using reflected light.

[0011] In examples, the locking reflective surface and emitting reflective surface may be mechanically supported by the same substrate. For example, the locking reflective surface and emitting reflective surface may be provided in a surface of the same substrate, such as being formed in the same substrate layer using an appropriate technique, such as focussed ion beam (FIB) milling or CO2 laser processing. Alternatively, the locking reflective surface and emitting reflective surfaces may be provided in different layers of the substrate, or in layers of material deposited on or fixed to the substrate, or in recessed surfaces formed in the substrate, for example by etching. Nevertheless, the locking reflective surface and emitting reflective surfaces may be supported by the same substrate. In examples, the locking reflective surface and emitting reflective surface may be on different substrates. In examples, the substrate comprising the emitting reflective surface may be mechanically coupled to the locking reflective surface of the substrate comprising the locking reflective surface. In examples, the emitting recess and locking recess may have different depths. In examples, the locking reflective surface and emitting reflective surface may be at different distances from the first reflective surface, such that the locking cavity has a different length to the emitting cavity. For example, the locking cavity may have a longer length than the emitting cavity. The locking reflective surface and emitting reflective surface may have different depths in the substrate or may be formed at different heights. This allows the locking laser to be decoupled from the single photon emission. By allowing the locking cavity to be formed to have different coupling characteristics to the emitting cavity, this allows the locking cavity to be optimised for a given mode locking technique, and the emitting cavity to be optimised for matching the resonant wavelength of the single photon emission, while also allowing the tuning of the locking cavity to lead to the tuning of the emitting cavity.

[0012] In examples, the emitting cavity may be to receive light from an excitation laser and the single photon emitter material may be to emit single photons in response to the received light from the excitation laser being incident on the material. In this way, the single photon emitting material in the cavity can be stimulated to emit a single photon. The single photon emitting material may be any material capable of emitting single photons in response to stimulation.

[0013] In examples, the emitter cavity and the locking cavity may be laterally spaced and substantially axially aligned. In this way, the tuning of the locking cavity by the actuator can also tune the emitting cavity, while the locking cavity is separated from the emitting cavity,

such that the locking laser light enters the locking cavity and not the emitting cavity. In examples, the locking cavity and emitting cavity may operate in different modes and may have different resonant wavelengths. In this way, the locking laser light would not be resonant with the emitting cavity and would be transmitted through it.

[0014] In examples, the emitting cavity may have a length in the range 0.3-10 μm and the locking cavity may have a length in the range 10-1000 μm. In examples, the emitting cavity may have a line width in the range 10-1000 GHz and the locking cavity may have a line width in the range 10-1000 MHz. In this way, the locking cavity may be optimised for use as a locking cavity using the Pound Drever Hall (PDH) technique, in which the locking cavity line width is lower than the emitting cavity line width, and in which the locking laser light is phase modulated using an electro optic modulator at a frequency significantly greater than the locking cavity line width, for example in the GHz range. Alternatively, the locking cavity may be optimised for use as a locking cavity using the side-locking technique, in which the locking reference is set to the steepest part of the side of the cavity mode and intensity change is monitored as the cavity mode drifts off the set point. This intensity change is then used to correct for frequency drift.

[0015] In examples, the apparatus may operate in a temperature range between 4K and room temperature. The cavity locking mechanism provided by the locking cavity and emitting cavity can operate at any temperature as it is temperature-insensitive. The temperature range of the apparatus may depend on the single photon emitter material used. Moreover, whilst the apparatus may operate within a particular temperature range, the chosen temperature at which to operate the apparatus may be the temperature at which the apparatus is most effective, that is, at which the apparatus most reliably generates a stable source of indistinguishable photons. For example, the apparatus may operate at a low temperature, for example below 0˚C, in order to achieve particular performance metrics.

[0016] In examples, the single photon emitter material may be a two dimensional material having a fluorescent defect or a quantum dot. In examples, the single photon material may be to emit single photons at temperatures in the range 0-20˚C. In examples, the single photon emitter material may comprise hexagonal Boron Nitride, hBN. Where the single photon emitter material is hBN, this enables the apparatus to operate in the temperature range of 0-20˚C. Whilst hBN also emits single photons at a much larger range of temperatures than the range 0-20˚C, and so the apparatus can operate at a large range of temperatures including temperatures significantly lower than 0-20˚C, being able to emit photons at room temperature increases the usefulness of the material. In other examples, the single photon emitter

material may comprise nanodiamond or layered transition-metal dichalcogenides. In other examples, the single photon emitter material may comprise a trapped ion or neutral atom, or a quantum object. In examples, the single photon emitter material may be a quantum object, for example a qubit in a quantum computer.

[0017] In examples, the single photons emitted from the single photon emitter material may have a wavelength of approximately 400nm or above. For example, the single photons emitted from the single photon emitter material may have a wavelength of between 550nm and 800nm.

[0018] In examples, tuning the length of the locking cavity may comprise adjusting the first reflective surface and/or the locking reflective surface. In examples, the actuator may be a piezo actuator. In examples, the actuator may be to tune the length of the locking cavity based on the phase of the portion of light output from the locking cavity. In examples, the locking cavity and emitting cavity may be Fabry-Perot cavities. In examples, the locking cavity may be to receive light from the locking laser that has been modulated in phase. In this way, the actuator may fine tune the length of the locking cavity to lock it to the stable locking laser. In examples, the actuator may actuate a portion of the apparatus providing the first reflective surface, a portion of the apparatus providing the locking reflective surface and/or a portion of the apparatus providing the emitting reflective surface.

[0019] Viewed from another example, the present disclosure provides a system for generating single photons. In particular, the system may be considered to provide a light-matter interface for enhancing transitions that generate single photons. The system comprising: an apparatus for generating single photons in accordance with examples of the present disclosure; and optics for transmitting light into the locking cavity of the apparatus.

[0020] In examples, the optics may comprise a locking laser to generate light for transmission into the locking cavity of the apparatus. In examples, the locking laser may be to generate light having a wavelength different to that of the single photon emission wavelength. In examples, the optics may further comprise a modulator to modulate the phase of the light generated by the locking laser and transmit the modulated light into the locking cavity of the apparatus. In examples, the modulator may be an electro optic modulator. In examples, the system may further comprise an RF driver coupled to the electro optic modulator and configured to output a modulation signal to drive the modulator to modulate the phase of the locking laser at a phase modulation frequency substantially greater than the linewidth of the locking cavity. In examples, the phase modulation frequency may be at least 1GHz. In examples, the optics may further comprise a coherent detector to

detect the portion of light output from the locking cavity of the apparatus and mix the detected light signal with the modulation signal from the RF driver to output a feedback signal based on the detected portion of light indicative of the drift of the locking cavity from the locking laser. In examples, the system may further comprise a controller configured to receive the feedback signal and output an error signal to the actuator of the apparatus based on the feedback signal, the actuator to tune the length of the locking cavity based on the error signal to maintain the locking cavity on resonance with the locking laser. In examples, the controller may be to output the error signal to the actuator of the apparatus based on the phase of the detected portion of light output from the locking cavity. In examples, the controller may be a proportional integral derivative (PID) controller. In examples, the system may be configured to control the actuator to lock the locking cavity to being on resonance with the locking laser using a Pound Drever Hall technique. In examples, the system may be configured such that the locking of the locking cavity to being on resonance with the locking laser causes a fundamental mode of the emitter cavity to be maintained on resonance with single photon emission frequency of the single photon emitter material. In examples, the system may further comprise a pulsed excitation laser and optics to direct light from the pulsed excitation laser to illuminate the single photon emitter material in the emitter cavity to trigger the emission of single photons at the fixed single photon emission frequency. In this way, the apparatus may be operated to maintain the single photon emitting material in an enhancement cavity at a stable long term frequency held on resonance with the single photon emitting frequency, without the locking laser light being coupled or mixed with the single photons, facilitating their detection.

[0021] In examples, the system may further comprise at least one further apparatus for generating single photons in accordance with examples of the present disclosure. In examples, the optics may be configured to transmit light into the locking cavities of each of the apparatuses from the same locking laser. In examples, the optics may be further configured to transmit light into the emitting cavities of each of the apparatuses from the same pulsed excitation laser, the photon emitter material of each apparatus to emit single photons in response to the received light from the excitation laser being incident on the material. In examples, the plurality of emitter cavities in the plurality of apparatuses may be for emitting single photons, each emitter cavity emitting single photons at substantially the same fixed single photon frequency responsive to illumination by an excitation laser. In this way, a plurality of single photon emitters provided in separate, tuneable, apparatuses, may all be tuned

together to stay on resonance long term with their single photon emission wavelengths based on the same, common, stable locking laser.

[0022] Viewed from another example, the present disclosure provides a method of manufacturing an apparatus for generating single photons, the method comprising: providing a locking substrate comprising a locking reflective surface; forming a recess in the locking reflective surface to form a locking cavity with a first reflective surface of a first substrate; providing an emitting substrate comprising an emitting reflective surface, the emitting substrate and locking substrate being mechanically coupled; forming a recess in the emitting reflective surface to form an emitting cavity with the first reflective surface of the first substrate; providing a single photon emitter material for emitting single photons located in the emitting cavity; providing the first substrate comprising the first reflective surface; and tuning the length of the locking cavity based on the cavity length of the locking cavity to tune the length of the emitting cavity into a fixed configuration, to be fine tuned by an actuator during use. In examples, the recesses may be formed using a focused ion beam.

[0023] Many modifications and other embodiments of the inventions set out herein will come to mind to a person skilled in the art to which these inventions pertain in light of the teachings presented herein. Therefore, it will be understood that the disclosure herein is not to be limited to the specific embodiments disclosed herein. Moreover, although the description provided herein provides example embodiments in the context of certain combinations of elements, steps and/or functions may be provided by alternative embodiments without departing from the scope of the invention.

Brief Description Of The Drawings

[0024] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which like reference numerals are used to depict like parts. In the drawings:

Figure 1 shows a schematic illustration of an apparatus for generating single photons in accordance with aspects of the present disclosure;

Figure 2A shows a first embodiment of an apparatus for generating single photons in accordance with aspects of the present disclosure;

Figure 2B shows a second embodiment of an apparatus for generating single photons in accordance with aspects of the present disclosure;

Figure 3 shows a schematic illustration of an embodiment of a system for use in generating single photons in accordance with aspects of the present disclosure;