Description

Title: DEVICE FOR DETECTING SINGLE MICROWAVE PHOTONS

Technical field

The invention is in the field of quantum sensors and more specifically relates to the field of instrumentation for measuring power in the microwave range of the electromagnetic spectrum.

The invention relates to a device for detecting single photons in the microwave range. The microwave range corresponds to photon frequencies of the order of 1 to 20 GHz.

The invention also relates to a method for detecting single microwave photons implemented by such a device.

Prior art

Single photon detection devices exist that are highly effective in the optical and infrared fields. These devices have very high detection efficiencies (with near-unity), low operating noise and almost continuous operating modes. They are notably implemented for carrying out quantum optics experiments, for example, for preparing non-conventional states, for generating entanglement, or for producing remotely shared cryptographic keys.

However, in the microwave range, photons are difficult to detect due to their very low energy. However, detecting electromagnetic power in the microwave range is a significant issue in various technological fields: telecommunications (notably 3G, 4G, Wi-Fi technologies), radar technologies, medical imaging or even chemical analysis (notably magnetic resonance) can be cited.

The use of quantum sensors allows single photons to be counted in the microwave domain and thus allows the corpuscular aspect of electromagnetic radiation to be solved. Power is detected by measuring the photon flux per unit of time. This results in power detection with optimal sensitivity.

The article entitled, "*Cyclically Operated Microwave Single-Photon Counter with Sensitivity of 1e-22 W / sqrt(Hz)*", by Balembois et al., PRApplied (2023) describes a single microwave photon detection device with a quantum bit.

Patent FR 3090891 B1 describes a device 1 for detecting a single microwave photon such as that shown in figure 1.

The detection device 1 is a superconducting circuit containing a superconducting quantum bit 10, or qubit, capable of assuming two quantum states, denoted |g> (for *ground*, or the ground state) and |e> (for *excited*, or an excited state). The quantum bit 10 has a transition frequency f_q. The energy difference between the states |g> and |e> is f_q . h, where h is Planck's constant.

The quantum bit 10 is represented by a capacitor arranged parallel to a Josephson junction in figure 1.

An input resonator 12 is coupled to a photon transmission line 16 and to the quantum bit 10. The input resonator 12 oscillates at a frequency f_a and allows an incident photon 2 to be collected.

An output resonator 14 is coupled to the quantum bit 10 and to a photon transmission line 18 by capacitive coupling 15. The output resonator 14 oscillates at a frequency f_b and allows an output photon 3 to be released following the detection of the incident photon 2.

The input and output resonators 12, 14 are each represented by a capacitor arranged parallel to an inductor in figure 1.

A microwave pump tone 4, i.e., a coherent signal oscillating at a frequency f_p, is applied to the qubit 10 in order to activate the detection process. The pump tone 4 is transmitted to the qubit 10 by a transmission line 20.

A microwave photon is detected when the quantum bit 10 is excited, which is caused by the photon passing through the detection device.

Indeed, initially, the incident photon 2 enters the input resonator 12.

The incident photon 2 then combines with the pump tone 4. This activates four-wave mixing in which the incident photon 2 is converted into an excitation of the quantum bit 10, which transitions from the ground state |g> to the excited state |e>, as well as an output photon 3 emitted in the output resonator 14.

This four-wave mixing process is possible when the parametric pumping frequency satisfies the conservation of the energy $f_p + f_a = f_q + f_b$. In other words, the energy of the incident photon 2 and of a photon of the pump tone 4 must be equal to the energy of the excitation of the quantum bit 10 and of an output photon 3.

The output photon 3 created in the output resonator is re-emitted as an outward propagating photon. Without the photon 3 in the output resonator, the quantum bit 10 cannot

return to the ground state by following the inverse four-wave mixing process: it therefore remains in the excited state.

Measuring the state of the quantum bit 10 is used to determine whether it is in the ground state or in the excited state, which corresponds to the detection of an incident photon 2. If the quantum bit 10 is measured in the excited state, a counting event is recorded and the quantum bit is reset to its ground state. The detection process can then resume.

However, the quantum bit 10 can be excited independently of the detection of a microwave photon. This can be caused, for example, by thermal noise, by a quasi-particle or by energetic radiation. In this case, a counting event will be recorded in the absence of an incident photon. These events therefore generate false positives, i.e., dark noise.

The main sources of dark noise are imperfections in the detector and thermal photons originating from the environment.

When the photon flux per unit of time is very low, the dark noise limits the sensitivity of the photon counting.

Dark noise can be reduced by minimizing spontaneous excitations of the quantum bit, for example, by improving the screening of the device, its thermalization or even by improving the nano-fabrication techniques of the device. However, these precautions are not always sufficient.

Moreover, in order to be sensitive, counting photons at microwave frequencies must be efficient. The probability of counting a detection event, when an incident photon impacts the input resonator, must be as high as possible, if possible arbitrarily close to unity.

The sensitivity of a microwave photon counting device can be quantified by a quantity denoted NEP (*Noise Equivalent Power*), which corresponds to the minimum detectable power with a signal-to-noise ratio of 1 for an integration time of one second. This quantity is expressed in $W.s^{1/2}$ and is defined for a photon counting device by the equation:

$$NEP = h.f_a.\sqrt{\alpha}/\eta$$

where h is the Planck's constant, f_a is the operating frequency of the detector, α is the dark count in Hz or s^{-1} and η is the efficiency of the detector, i.e., the probability of obtaining a detection signal when a photon reaches the detector.

Patent US 9692423 B2 relates to a system for reading quantum bits that allows a number of incident microwave photons to be counted in a non-destructive manner.

A requirement exists for a single microwave photon detection device that minimizes dark noise while providing high efficiency.

The aim of the invention is to at least partially meet this requirement.

Disclosure of the invention

To this end, the invention relates, according to one aspect thereof, to a single microwave photon detection device, comprising:

- a multi-state quantum system comprising N qudit(s), with N being greater than or equal to 1, the system being capable of performing, in response to receiving an incident microwave photon, a number X of energy transitions between energy levels distributed between the one or more N qudits that is greater than or equal to 2, with these energy transitions corresponding to respective frequencies f_1, …, f_X;
- a set of resonators defining X+1 electromagnetic modes of respective frequencies $f_{M,1}$ to $f_{M,X+1}$;
- a parametric pumping system for applying X pump tones of respective frequencies $f_{p,i}$, verifying $f_{M,i} + f_{p,i} = f_i + f_{M,i+1}$, with each integer i ranging from 1 to X, so as to frequency convert, by parametric pumping, the excitation contained in an electromagnetic mode i into an excitation of the electromagnetic mode i+1 and a transition i of the relevant qudit;
- a system for reading the energy levels of the one or more qudits of the quantum system providing information concerning whether or not an incident microwave photon has been received.

The term “qudit” denotes a quantum subsystem with at least two energy levels, i.e., capable of performing at least one energy transition. A qubit is a two-level qudit. A “qubit” thus has a ground state and an excited state.

The detection device is thus configured to convert a photon of the electromagnetic mode M_i and a pump tone of frequency $f_{p,i}$ into an excitation of the qubit Q_i and a photon of the electromagnetic mode M_{i+1}, for i ranging between 1 and X inclusive.

The conversion process is known per se, being notably described in patent FR 3090891. It is activated by combining the photon of the electromagnetic mode M_i and the pump tone of frequency $f_{p,i}$ and involves an adaptable interaction with four waves.

The pump tone of frequency $f_{p,i}$ is preferably applied to the qubit Q_i.

Preferably, the detection device is configured so that the conversion of the photon of the electromagnetic mode M_X into an excitation of the qubit Q_X has a transfer rate Γ_X that is less than or equal to the dissipation rate κ_w of the electromagnetic output mode M_{X+1}.

The incident photon can be transmitted to the input resonator via a transmission line coupled to this input resonator. The output photon of the output resonator can be discharged by a transmission line coupled to this resonator.

The frequency of the incident photon can range between 1 and 25 GHz, advantageously between 1 and 20 GHz. In particular, it can range between 4 and 8 GHz.

The detection device is preferably operated at a cryogenic temperature of less than 1 K, preferably of less than 20 mK, notably of the order of 10 mK. The quantum bits preferably are superconducting quantum bits.

Preferably, the set of resonators comprises X+1 resonators defining the X+1 electromagnetic modes. Alternatively, the set of resonators comprises a number of resonators that is less than X+1 that define the X+1 electromagnetic modes. In other words, according to this variant, some resonators define more than two electromagnetic modes.

The quantum system can comprise at least one qudit on which more than one transition occurs, notably two transitions, or even the X energy transitions.

The quantum system can comprise at least two spatially distinct qudit, between which the X energy transitions are distributed. For example, at least one of the two qudits is a qubit. The two qudits can be qubits. At least one of the two qudits can have at least three energy levels, namely, a ground level and two excited levels.

The quantum system can comprise a qubit on which one of the energy transitions occurs and a qudit with at least three levels on which at least one other energy transition occurs.

The one or more qudits preferably is/are transmon type superconducting qudits.

The reading system can measure the state of each qudit. Alternatively, the reading system returns logical information concerning the state of the quantum system as a whole, without providing information specific to the individual state of each qudit.

For example, the reading system comprises at least one reading resonator, the one or more reading resonators being coupled to one or more of the corresponding qudits. The photon detector can comprise at least as many reading resonators as qudits.

The system can comprise an input resonator coupled to a source of microwave photons and an output resonator coupled to a dissipative environment adapted to dissipate a microwave photon.

The input resonator can comprise a SQUID device configured to tune the frequency of the input resonator. This improves detection efficiency.

The output resonator can form one of the reading resonators of the reading system.

Another aspect of the invention relates to a method for detecting an incident single microwave photon using a microwave photon detection device, notably as defined above, the device comprising a multi-state quantum system comprising N qudit(s), with N being greater than or equal to 1, the system being capable of performing, in response to receiving an incident microwave photon, a number X of energy transitions between energy levels distributed between the one or more N qudits that is greater than or equal to 2, with these energy transitions corresponding to respective frequencies f_1, …, f_X, the method comprising the following steps of:

a/ applying X pump tones of respective frequencies $f_{p,\,i}$, verifying $f_{M,i} + f_{p,i} = f_i + f_{M,i+1}$, with each integer i ranging from 1 to X, so as to frequency convert, by parametric pumping, the excitation contained in an electromagnetic mode i into an excitation of the electromagnetic mode i+1 and a transition i of the relevant qudit;

b/ reading the energy levels of the one or more qudits of the quantum system and deducing information therefrom concerning whether or not an incident microwave photon has been received by the detector.

At least one of the energy transitions can be a transition of a qubit from a ground state to an excited state.

At least one of the energy transitions can be a transition of a qudit from a ground state to an excited state or between two successive excited states.

The step of reading the energy levels of the one or more qudits can involve detecting whether a majority of energy transitions have occurred in the quantum system. Optionally, the quantum system comprises an odd number X of energy transitions.

The step of reading the states of the one or more qudits can involve detecting whether the X energy transitions have actually occurred.

The method can comprise, prior to step a/, a step of adjusting the passband of the quantum system in which the amplitude A_i of the frequencies of the pump tones is determined so as to adjust said passband to a desired value.

Another aspect of the invention relates to a device for detecting a single microwave photon comprising:

- a number N of quantum bits Q_1, …, Q_N that is greater than or equal to 2 with two energy levels whose ground state and an excited state are controllable and detectable, the transition between the ground and excited states of each quantum bit Q_i having a frequency $f_{q,i}$ for i ranging between 1 and N inclusive;
- an input resonator R_1 configured to receive an incident single microwave photon and having a frequency $f_{r,1}$, the input resonator being coupled to a first quantum bit Q_1 of the N quantum bits;
- an output resonator R_{N+1} configured to discharge an output photon and having a frequency $f_{r,N+1}$, the output resonator being coupled to an N-th quantum bit Q_N of the N quantum bits;
- a number (N-1) of bus resonators R_j configured to transmit an intermediate photon from the quantum bit Q_{j-1} to the quantum bit Q_j and each having a frequency $f_{r,j}$, for j ranging between 2 and N inclusive;
- a number N of reading systems, each coupled to one of the N quantum bits, for detecting the state of said quantum bit;
- a number N of parametric pumping transmission lines each configured to transmit a pump tone to one of the N quantum bits and/or to one of the input, output or bus resonators, so that a photon of an input or bus resonator R_i and a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} - f_{r,i}$ can be converted into an excitation of the quantum bit Q_i and a photon of the bus or output resonator R_{i+1}, for i ranging between 1 and N inclusive.

By virtue of the detection device according to the invention, dark noise is significantly reduced. Indeed, the redundancy due to the use of a plurality of qudits allows any false positives caused by an unwanted excitation of the qudits to be limited. The impact of an incident photon on the detection device triggers a cascade of excitation of the qudits. Consequently, the detection of a photon can only be counted when the reading system detects that at least a majority of possible energy transitions have actually occurred. An event that

triggers only one energy transition or only a minority of energy transitions therefore can be identified as dark noise and can be discarded.

In a particular case where the quantum system comprises a string of qubits, the detection of a photon is only counted when at least several of the quantum bits are simultaneously measured in their excited state. An event that would only trigger the excitation of a quantum bit or of a minority of quantum bits therefore can be identified as dark noise and discarded.

Furthermore, when the environment of the detection device is not sufficiently cooled, it can be populated with thermal photons that can cause erroneous counting and thus generate dark noise. As will be seen hereafter, the detection device according to the invention allows dynamic adjustment of its passband to the frequency of the signal to be measured. This significantly reduces thermal dark noise.

According to one advantageous feature, the N quantum bits are transmon type superconducting quantum bits.

According to another advantageous feature, each reading system comprises a resonator.

Preferably, the reading system coupled to the N-th quantum bit Q_N comprises the output resonator R_{N+1}. A specific reading resonator then does not need to be coupled to the last quantum bit Q_N, since the output resonator R_{N+1} allows the state of the qubit to be read.

Alternatively, the reading system coupled to the N-th quantum bit Q_N is distinct from the output resonator R_{N+1}.

Advantageously, the input resonator, the output resonator and the bus resonators are superconducting microwave resonators.

According to one advantageous feature, the input resonator is coupled to a source of microwave photons and the output resonator is coupled to a dissipative environment adapted to dissipate a microwave photon.

Advantageously, the input resonator can comprise a SQUID device configured to tune the frequency of the input resonator.

The invention also relates to a method for detecting a single microwave photon implemented by means of a detection device as described above, comprising the steps of:

a/ applying a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} - f_{r,i}$, to each quantum bit Q_i, for i

ranging between 1 and N inclusive;

b/ measuring the state of each quantum bit Q_i.

According to an advantageous embodiment, the detection device comprises an odd number of quantum bits, and the method comprises, after step b/, a detection step c/ involving determining whether at least a majority (N+1)/2 of the quantum bits is measured in the excited state, in which case a detection event is counted.

Alternatively, the method comprises, after step b/, a detection step c1/ involving determining whether all the quantum bits are measured in the excited state, in which case a detection event is counted.

According to one advantageous feature, the method comprises, prior to step a/, a step a0/ of adjusting the passband of the detection device in which the amplitude A_i of the pump tones of frequency $f_{p,i}$ is determined so as to adjust said passband to a desired value.

By adjusting the amplitude of the pump tones, the passband of the detection device can be adjusted. The properly selected adaptation of the passband of the device to the frequency of the photons to be detected allows the thermal dark noise to be significantly reduced.

Preferably, the amplitudes A_i of the pump tones are selected so that the transfer rates Γ_i of photons in the resonators R_i are all equal to the same value Γ. The passband of the device is then determined by the value of Γ.

Thus, in order to detect an incident microwave photon, the latter is initially received in the input resonator of the detection device. In combination with the application of parametric pumping, the incident photon is converted into an excitation of the first quantum bit and a photon in the bus resonator coupled to the first quantum bit. This intermediate photon, in combination with the application of parametric pumping, is itself converted into an excitation of the next quantum bit and a photon. In the same way, all the quantum bits of the detection device are excited. A step of reading the state of the quantum bits then allows the detection of an incident photon to be confirmed.

Brief description of the drawings

[Figure 1] Figure 1 shows a device for detecting single microwave photons according to the prior art.

[Figure 2] Figure 2 schematically shows a microwave photon detection device according to the invention.

[Figure 3] Figure 3 schematically shows the operation of the detection device according to one embodiment of the invention.

[Figure 4] [Figure 5] Figures 4 and 5 schematically illustrate the operation of the detection device according to a second embodiment of the invention.

[Figure 6] Figure 6 schematically illustrates the detection device according to a third embodiment of the invention.

[Figure 7a] Figure 7a schematically illustrates the excitation of a qudit in a first excited level.

[Figure 7b] [Figure 7c] [Figure 7d] Figures 7b to 7d are graphs illustrating the measurements taken on the qudit in the first excitation level.

[Figure 7e] Figure 7e schematically illustrates the qudit of figure 7a in the ground state.

[Figure 7f] [Figure 7g] [Figure 7h] Figure 7f to 7h are graphs illustrating measurements taken on the qudit in the ground state.

[Figure 8a] Figure 8a schematically illustrates the qudit brought to the second excitation level.

[Figure 8b] [Figure 8c] [Figure 8d] Figures 8b to 8d are graphs illustrating the measurements taken on the qudit in its second excitation level.

[Figure 8e] Figure 8e schematically illustrates the measurements taken on the qudit in its first excitation level.

[Figure 8f] [Figure 8g] [Figure 8h] Figures 8f to 8h are graphs illustrating the measurements taken on the qudit in its first excitation level.

[Figure 9a] Figure 9a schematically illustrates a qudit brought to the second excited level.

[Figure 9b] [Figure 9c] [Figure 9d] Figures 9b to 9d are graphs illustrating the measurements taken on the qudit in its second excited level.

[Figure 9e] Figure 9e schematically illustrates the qudit in its ground level.

[Figure 9f] [Figure 9g] [Figure 9h] Figures 9f to 9h are graphs illustrating the measurements of the qudit in its ground state.

[Figure 10] Figure 10 represents a particular case of a device for detecting single microwave photons according to the invention.

[Figure 11] Figure 11 shows a variant of the particular case of the device for detecting single microwave photons illustrated in figure 10.

[Figure 12] Figure 12 is a graph illustrating the probability of detecting excitation of the first quantum bit of the device of figure 11 in the presence of a probe signal.

[Figure 13] Figure 13 is a graph illustrating the probability of detecting excitation of the first quantum bit of the device of figure 11 in the absence of a probe signal.

[Figure 14] Figure 14 is a graph illustrating the probability of detecting excitation of the second quantum bit of the device of figure 11 in the presence of a probe signal.

[Figure 15] Figure 15 is a graph illustrating the probability of detecting excitation of the second quantum bit of the device of figure 11 in the absence of a probe signal.

[Figure 16] Figure 16 is a graph illustrating the probability of simultaneously detecting excitation of the first and second quantum bits of the device of figure 11 in the presence of a probe signal.

[Figure 17] Figure 17 is a graph illustrating the probability of simultaneously detecting excitation of the first and second quantum bits of the device of figure 11 in the absence of a probe signal.

[Figure 18] Figure 18 illustrates the response of the quantum bits of the device of figure 11 to a first photon flux.

[Figure 19] Figure 19 illustrates the response of the quantum bits of the device of figure 11 to a second photon flux.

[Figure 20] Figure 20 illustrates the response of the quantum bits of the device of figure 11 to a third photon flux.

[Figure 21] Figure 21 shows a third embodiment of a detection device according to the invention.

Detailed description

Figure 1 has been described in the preamble and will not be discussed hereafter.

For the sake of clarity, the same elements of a device for detecting single microwave photons according to the prior art and of a detection device according to the invention are designated using the same numerical references.

Figure 2 schematically shows a device 100 for detecting a single microwave photon according to the invention, comprising a quantum system with N qudit(s) $Q_{d,1}$ to $Q_{d,N}$, with N being greater than or equal to 1. The quantum system is capable of performing a number X of energy transitions between energy levels that is greater than or equal to 2, with these transitions being distributed between the one or more N qudits, and corresponding to respective frequencies $f_1, \ldots, f_X$. In order to perform the X energy transitions, the device 100 comprises N subsystem(s), each comprising:

- a qudit $Q_1 \ldots Q_N$;
- a set of resonators R together defining at least two electromagnetic modes M;
- at least one transmission line 20 configured to transmit a number k ranging between 1 and X of pump tones 4 to the one or more relevant qudits, with each pump tone 4 allowing parametric pumping to be performed with a frequency f_p that is selected so as to allow four-wave mixing, transitioning the relevant qudit Q_i from one energetic state to another;
- at least one reading resonator 10 for detecting the state of the relevant qudit.

As shown, each subsystem i is coupled to the next subsystem i+1 by a shared electromagnetic mode M_i.

The first subsystem differs from the following subsystems in that it is coupled to a photon transmission line 16 that is configured to transmit incident microwave photons 2 to the first electromagnetic mode M_1, in this case housed in an input resonator R_1. The transmission line 16 is coupled to the input resonator R_1 with a rate κ_b. By way of an example, $\kappa_b/(2\pi)$ can be of the order of 1 MHz. The transmission line 16 notably can couple a source of microwave photons to the input resonator R_1.

One operation of the device can be as follows.

The number X of desired energy transitions is defined beforehand. The frequencies of the pump tones 4 to be applied to each subsystem are also defined beforehand so that $f_{M,i} + f_{p,i} = f_i + f_{M,i+1}$, with $f_{M,i}$ being the frequency of the electromagnetic mode M_i, $f_{p,i}$ being the

frequency of the pump tone P_i, f_i being the frequency of the energy transition i and $f_{M,i+1}$ being the frequency of the electromagnetic mode M_{i+1}.

All the pump tones 4 are applied when the device 100 is started.

In the case whereby an incident microwave photon joins the first resonator R_1, applying the first pump tone causes a first energy transition of the first qudit $Q_{d,1}$, which results in the generation of a first resultant photon that propagates in the second resonator R_2. Applying the second pump tone results in a second energy transition that generates a second resultant photon that propagates in the third resonator, so that the X energy transitions can occur.

The N^{th} subsystem is coupled to the output resonator R_{X+1} configured to transmit an output photon 3 to an output transmission line 18. The output resonator R_{X+1} is coupled to the output transmission line 18 with a dissipation rate κ_w. The dissipation rate is high compared to the transfer rate Γ, with, for example, a rate $\kappa_w/(2\pi)$ of the order of 3 MHz for a conversion rate of the order of 200 kHz, which makes the output resonator highly dissipative, and allows the photon created in the output resonator R_{X+1} to be rapidly transmitted to the transmission line 18. Therefore, the reverse conversion process, which would cause the detection signal to disappear, is avoided.

The transmission line 18 can thus couple the output resonator R_{X+1} to a dissipative environment, which can be a cold load, such as an object cooled to a cryogenic temperature.

The X energy transitions are distributed over the one or more N qudits. Thus, a qudit can undergo between one and X changes of state, depending on the number of pump tones applied thereto.

Each subsystem can comprise a reading resonator 10, as illustrated, allowing the state of the relevant qudit to be determined.

Thus, once all the pump tones have been applied, for a predefined period, they are switched off to allow the reading system to read the states of the one or more qudits. The device then determines, based on the information provided by this reading system, whether an incident photon has actually passed through the device.

For example, the detection of a majority of energy transitions compared to the number of predefined energy transitions leads to the conclusion that an incident photon has actually passed through the device. Conversely, the detection of a minority of energy

transitions compared to the number of predefined energy transitions leads to the conclusion that there is no incident photon. It is understood that this is only an example and that any other threshold can be applied. For example, the device can be configured to conclude that an incident photon is present only if all the energy transitions have actually occurred.

Figure 3 illustrates an example of a detection device 100 according to the invention, in which the system comprises a single three-state qudit Q.

In this case, the operation of the device is as follows.

It is previously determined that X = 2 energy transitions are expected. Two pump tones are then determined, the frequencies of which are such that: $f_{M,1} + f_{p,1} = f_1 + f_{M,2}$ and $f_{M,2} + f_{p,2} = f_2 + f_{M,3}$.

When the device is started, the pump tones of respective frequencies f_1, f_2 are applied.

If an incident photon 2 is present in the input resonator R_1, then the qudit Q undergoes, by parametric pumping, a first energy transition i_1 from its ground state to a first excited state, generating a first resultant photon P_{R1}, which propagates in the second resonator R_2. The qudit in its first excited state also undergoes, by parametric pumping, a second energy transition i_2 from its first excited state to its second excited state, generating a second resultant photon P_{R2}, which propagates in a third resonator R_3, which forms an output resonator. Once the pump tones are switched off, the reading resonator 10 is used to determine the state of the qudit Q. If the qudit Q is in its second excited state, then it is concluded that an incident photon was indeed present. If the qudit Q remained in its ground state it is concluded that no incident photon was present. Finally, if the qudit Q is in its first excited state, it is concluded that it is most likely a dark noise, and that no incident photon was actually present.

The term “use of the reading resonator” in this case refers to sending a microwave pulse into the reading resonator, with this pulse probably containing several photons. The pulse is reflected with an additional phase dependent on the state of the qudit.

Figures 4 and 5 schematically illustrate a variant of the device comprising two qudits Q1, Q2. Four energy transitions are desired, so that four pump tones of respective frequencies f1, f2, f3, f4 are applied to the system.

As illustrated in figure 5, the second resultant photon P_{R2} that is obtained as described with reference to figure 3 and propagates in the third resonator R_3, in this case is

transformed, by parametric pumping during a third energy transition i_3, into a third resultant photon P_{R3}, which propagates in a fourth resonator R_4, with this third energy transition corresponding to a first energy transition of the second qudit Q_2 that transitions from the ground state to the first excited level. A fourth energy transition i_4 can take place on the second qudit Q_2, with this fourth energy transition corresponding to a second energy transition of the second qudit Q_2, which transitions from the first excited level to the second excited level. This fourth transition of the overall quantum system generates a fourth resultant photon P_{R4}, which propagates in a fifth resonator R_5, which in this case forms the output resonator.

The pump tones are then deactivated to allow the states of the two qubits Q_1, Q_2 to be read and to conclude whether the incident photon is present or absent. For example, if both qudits are detected as each being in their second excited state, it is possible to conclude that an incident photon is present.

Figure 6 illustrates another variant of the device 100 according to the invention where the system comprises a first three-state qudit Q'1 and a second two-state qudit Q'2, also called "qubit". This corresponds to N = 2 (2 qudits in total), X = 3 (three transitions in total), k = 3 (3 levels or 2 transitions) and K = 2 (2 levels or one transition) in the diagram of figure 2.

In this example, the intention is for a total of three transitions to be made in the system in case an incident photon is detected, and pump tones are defined beforehand at three frequencies f'1, f'2, f'3, with the first and second pump tones f'1, f'2 being applied by a first transmission line 20 and the third pump tone being applied by a second transmission line 21.

The pump tones sent through the transmission lines 20, 21 are activated to allow, in the presence of an incident photon, the energy transitions to be performed. In this case, the first energy transition corresponds to a first transition of the first qudit Q'1, which transitions from the ground state to the first excited level, the second energy transition corresponds to a second transition of the first qudit Q'1, which transitions from the first excited state to the second excited state and the third energy transition corresponds to a first transition of the second qudit Q'2, which transitions from the ground state to the first excited state.

Once the pump tones have been switched off, the reading system is used to determine the states of the qudits Q'1, Q'2 of the system and to conclude that the incident photon is present or absent.

Figures 7a to 7h illustrate an experimental embodiment using 4-wave mixing for a detector with a single three-state qudit. Figures 7b to 7d and 7e to 7h show the probabilities as a function of the frequency values (first pump frequency on the ordinate and second pump frequency on the abscissa). The qudit is initialized in its ground state 0, a single pump signal is applied (figures 7a to 7d) or not applied (figures 7e to 7h) so that the incident photon propagating in the first resonator R_1 is converted, or not converted, into a first resultant photon P_{R1} propagating in the second resonator R_2.

Figures 7b and 7f illustrate the probability of finding the qudit in its ground state, respectively, when a pump tone of frequency f1 is applied and when a pump tone is not applied. It should be noted that the probability is very high and homogeneous for all the frequencies in figure 7f, while a band indicates a very low probability at the frequency f1 in figure 7b. Figures 7c and 7g illustrate the probability of finding the qudit in its first excited state 1, respectively, when a pump tone of frequency f1 is applied and when a pump tone is not applied. It should be noted that the probability is homogeneous and very low for all the frequencies in figure 7g, while a band indicates a very high probability at the frequency f1 in figure 7c. Therefore, these four figures can be used to deduce that applying the pump tone f1 allows the energy transition of the qudit to occur from its ground state to its first excited state. Figures 7d and 7h illustrate the probability of finding the qudit in its second excited state, respectively, when a pump tone of frequency f1 is applied and when a pump tone is not applied. It should be noted that the probability is homogeneous and very low for all the frequencies in the two figures. A faint band is visible in figure 7d, related to inaccuracies in the monitoring and reading processes of the system. Figures 8a to 8h illustrate an experimental embodiment using 4-wave mixing for a detector with a single three-state qudit. Figures 8b to 8d and 8e to 8h show the probabilities as a function of the frequency values (first angular pump frequency on the ordinate and second angular pump frequency on the abscissa).

The qudit is initialized in its "1" state, a single pump signal is applied (figures 8a, 8b, 8c, 8d) or not applied (figures 8e, 8f, 8g, 8h) so that the photon present in the

intermediate mode defined by the resonator R_2 is converted, or not converted, in the output mode defined by the resonator R_3.

Figure 8a illustrates the 2nd conversion mechanism, with the qudit ending in its "2" state. In this experiment, the levels of the qudit each can be read individually. The experiment involves scanning the 2nd pump frequency ($\omega_2/2\pi$), at fixed amplitudes, knowing that the first is switched off, i.e., at zero amplitude (and at the frequency $\omega_1/2\pi$)). The probability of the qudit being measured in its "0" state (figures 8b, 8f), in its "1" state (figures 8c, 8g), or in its "2" state (figures 8d, 8h) was measured.

Figures 8b, 8c and 8d show that at a single frequency of the 2nd pump a population transfer of the qudit from its level 1 (depletion D) to its state 2 (vertical line L) is observed. The population in state 0 is almost zero.

Figures 8f, 8g, 8h confirm that the transfer 1→ 2 of the state of the qudit is indeed due to the application of the 2nd pump by adjusting its zero intensity while sending photons into the intermediate resonator.

Figures 9a to 9h illustrate an experimental embodiment using 4-wave mixing for a detector with a single three-state qudit. Figures 9b to 9d and 9e to 9h show the probabilities as a function of the frequency values (first angular pump frequency on the ordinate and second angular pump frequency on the abscissa).

The qudit is initialized in its "0" state, two pump signals are applied (figures 9a, 9b, 9c and 9d) or not applied (figures 9e, 9f, 9g and 9h) so that the photon present at the input (input mode defined by the resonator R_1) is converted, or not converted, in the output mode defined by the resonator R_3.

Figure 9a illustrates the overall conversion mechanism, with the qudit ending in its second excited state "2". In this experiment, each of the levels of the qudit can be read individually. The experiment involves scanning pump frequencies ($\omega_1/2\pi$ and $\omega_2/2\pi$), at fixed amplitudes. The probability of the qudit being measured in its "0" state corresponds to figures 9b, 9f, in its "1" state to figures 9c, 9g, or in its "2" state to figures 9d, 9h.

Figures 9b, 9c and 9d show that at a single frequency of the 1st pump a population transfer of the qudit from its level 0 (depletion D) to its state 1 (horizontal line L) is observed. The population in state 1 itself exhibits depletion at a single 2nd pump frequency, signifying the transfer between states 1→ 2 of the qudit (bright central zone C in figure 9d). The non-

zero population in the state 1 results from error induced by the decoherence of the transition 2→1.

Figures 9f, 9g and 9h confirm that the transfer 0→ 2 of the state of the qudit is indeed due to the application of the pumps by adjusting its zero intensities, while sending photons to be detected to the input of the detector.

Figures 10 and 11 illustrate a particular case in which the system exclusively comprises qubits, i.e., quantum subsystems capable of performing exactly one energy transition each. Then, the number X of energy transitions is equal to the number N of qudits of the quantum system.

For example, in figure 10, the first qubit Q_1 is coupled to a successive qubit Q_i via a bus resonator R_i configured to transmit an intermediate photon 5 from the quantum bit Q_1 to the quantum bit Q_i.

The device 100 can comprise one or more intermediate quantum bits, with each quantum bit Q_i being coupled to the next quantum bit Q_{i+1} by a bus resonator R_{i+1}. Each quantum bit Q_i is also coupled to a transmission line 20 allowing a pump tone 4 to be transmitted to the quantum bit Q_i and to a reading resonator 10 allowing the state of the quantum bit Q_i to be read.

The quantum bit Q_{N-1}, i.e., the last of the intermediate quantum bits Q_i, is coupled to the N-th quantum bit Q_N by a bus resonator R_N.

The N quantum bits of the device are thus connected in series by the bus resonators.

The N-th quantum bit Q_N is coupled to a transmission line 20 allowing a pump tone 4 to be transmitted to the quantum bit Q_N as well as to a reading resonator 10.

It is also coupled to an output resonator R_{N+1}.

The input, output, reading and bus resonators notably can be superconducting microwave resonators.

The quantum bits $Q_1, \ldots, Q_N$ notably can be transmons.

Within the scope of the invention, a transmission line notably can be a coplanar waveguide, in particular made of a superconducting metal.

The couplings between two elements of the detection device are preferably capacitive couplings.

The output resonator R_{N+1} advantageously can be used as a reading resonator, in which case a specific reading resonator does not need to be provided for the last quantum bit Q_N.

In a particularly advantageous manner, the amplitude A_i of the pump tone of frequency $f_{p,i}$ applied to the quantum bit Q_i can be adjusted. Indeed, the passband of the detection device according to the invention can be dynamically modified when the amplitudes A_i of the pump tones are modified. It is thus possible to adjust the width of the passband so as to integrate more or less input signal. This notably allows the signal-to-noise ratio of the input signal to be controlled.

The amplitudes A_i of the pump tones therefore can be determined so as to allow the quantum bits to be excited and a passband to be selected.

The four-wave Hamiltonian coupling of the device, when pumps are applied to the four-wave mixing frequencies, is:

$$H = \sum_i g_i A_i (r_i q_i^\dagger r_{i+1}^\dagger + r_i^\dagger q_i r_{i+1})$$

where r_i and q_i are respectively the destruction quantum operators associated with the resonator R_i and with the qubit Q_i, $r_i^\dagger$ and $q_i^\dagger$ are respectively the creation quantum operators associated with the resonator R_i and with the qubit Q_i, A_i is the amplitude of the pump applied to the qubit Q_i and g_i is the four-wave mixing rate associated with the qubit Q_i.

The four-wave mixing rate g_i depends on the coupling between the components of the device according to the relationship:

$$g_i = \sqrt{\chi_i^i \chi_{i+1}^i}$$

where χ_j^i is the dispersive offset between the qubit Q_i and the resonator R_j.

The transfer rate of a photon in each resonator can be computed based on this Hamiltonian. The pump amplitude applied to the qubit Q_i allows the transfer rates Γ_i, Γ_{i+1} of a photon to be adjusted, respectively in the resonators R_i and R_{i+1} according to the following relationship:

$$|g_i A_i|^2 = \Gamma_i \Gamma_{i+1}$$

In the case of the input resonator R_1 and of the output resonator R_{N+1}, this relationship respectively becomes:

$$|g_1 A_1|^2 = \kappa_b \Gamma_2$$

and

$$|g_N A_N|^2 = \Gamma_N \kappa_w$$

Preferably, in order to obtain optimum transmission of the photon in the series of resonators, the pump amplitudes A_i are adjusted so that the transfer rates Γ_2, …, Γ_N are all equal to a value Γ.

The transfer rate and the passband of the device are then determined by Γ and the theoretical efficiency of the device is 1.

Preferably, for optimal operation of the device, the dispersive offsets of the device are determined so that, for i ranging between 1 and N inclusive:

$$g_i^2 = \chi_i^i \chi_{i+1}^i \gg \Gamma$$

For example, a value of g_i^2 that is more than 5 times, 10 times or 20 times the value of Γ is selected.

The value of Γ can be adjusted while maintaining a theoretical efficiency of 1 as long as the relationship $\Gamma < \min(\kappa_b, \kappa_w)$ is respected.

Standard techniques can be implemented for manufacturing a detection device according to the invention.

The device 100, 100’ can be manufactured on a silicon wafer that is a few hundred micrometers thick, covered with a layer of niobium that is of the order of 100 nm thick. The quantum bits and the input, output and bus resonators can be lithographed on the niobium layer. The lengths of the resonators are selected as a function of the desired frequencies.

The detection of a single microwave photon by means of the detection device as shown in figures 10 and 11 occurs as follows.

Firstly, an incident microwave photon 2 is received in the input resonator R_1 of frequency $f_{r,1}$. The reception occurs at a rate κ_b. The incident photon 2 can be detected if its frequency is within the interval ($f_{r,1} \pm \Gamma_1/2$).

The incident photon 2 is then transmitted to the quantum bit Q_1. It is converted with a rate Γ_1 into an excitation of the quantum bit and an intermediate photon 5 of the bus resonator R_2 by virtue of the parametric pumping of the quantum bit Q_1.

The intermediate photon 5 of the bus resonator R_2 is transmitted to the next quantum bit Q_2 and the same conversion process is repeated. For a quantum bit Q_i of the

device where i ranges between 2 and N-1 inclusive, the photon emitted in the bus resonator R_i is converted with a rate Γ_i into an excitation of the quantum bit Q_i and an intermediate photon 5 of the bus resonator R_{i+1}.

The intermediate photon 5 of the bus resonator R_N is converted with a rate Γ_N into an excitation of the quantum bit Q_N and an output photon 3 of the output resonator R_{N+1}.

The ground state and the excited state of a quantum bit Q_i of the device are separated by an energy $f_{q,i}$. h, where h is the Planck's constant.

For i ranging between 1 and (N+1) inclusive, an input, output or bus resonator R_i of the device has a frequency $f_{r,i}$.

Preferably, the dissipation rate κ_w of the output resonator R_{N+1} is greater than the transfer rate Γ_N. This allows the output photon 3 to be rapidly transmitted to the transmission line 18 and therefore effectively inhibit the reverse photon conversion process that would make the quantum bit Q_N transition from the excited state to the ground state.

The state of each quantum bit is determined by this quantum bit being read by the associated reading resonator 10. The step of reading the quantum bits can be performed at the same time as the photon reception and conversion steps or after these steps. In the latter case, the reading step can be carried out in the absence of parametric pumping, which allows the output resonator 14 to be used as a reading resonator.

A step of resetting the quantum bits to their ground state can be carried out after reading their state in order to prepare the device to receive a new incident photon 2. The quantum bits can be reset by exciting bus resonators with a microwave pulse that is selected so as to allow the excitation of a quantum bit to be converted into a propagating photon. Preferably, the pumping frequency is selected so that the excitation of a quantum bit and the pulse on the associated bus resonator are converted into a photon of the associated reading resonator.

The quantum bits also can be reset by applying a microwave pulse to each quantum bit to be reset via the parametric pumping transmission line, with this pulse being determined so as to return the quantum bit from its excited state to its ground state.

It is also possible to wait for the natural relaxation of the quantum bits, although the transfer rates of an active reset are much higher than the relaxation rates of the quantum bits.

Thus, an incident photon 2 reaching the detection device 100 generates the excitation of N successive qubits rather than that of a single qubit.

According to a first alternative, the detection of an incident photon is counted when the N quantum bits are measured in their excited state. Since the spontaneous excitation events of the quantum bits are independent, the probability of detecting a false positive corresponds to the probability of simultaneously measuring the N quantum bits in their excited state, i.e., to a probability p_{th}^{N}, where p_{th} represents the probability of a spontaneous excitation of a quantum bit.

Therefore, the dark noise is significantly reduced compared with a detection device of the prior art.

Advantageously, a more sophisticated incident photon detection method can be implemented in order to minimize the inefficiency of the detection device, i.e., any false negatives corresponding to the probability of not counting an event when an incident photon 2 reaches the detection device.

The main process contributing to the inefficiency of the device is the spontaneous de-excitation of a quantum bit. These events are independent for each of the quantum bits. $\bar{\eta} = (1 - \eta)$ Denotes the probability of a spontaneous de-excitation of a quantum bit. The probability of having at least one spontaneous de-excitation from among the N quantum bits is then $1 - (1 - \bar{\eta})^N \approx N\bar{\eta}$ for $\bar{\eta} \ll 1$. Therefore, this probability significantly increases with the number of quantum bits.

For an odd number N, an advantageous detection method involves counting a detection only if a majority of quantum bits are measured in their excited state. For an even number N greater than 3, it is possible to count a detection only if half N/2 or majority N/2+1 of the quantum bits are measured in their excited state.

This thereby avoids being limited to the case where all the quantum bits are measured in their excited state. In this way, the probabilities of false positives and of false negatives both can be kept arbitrarily low: when N is odd, the probability of detecting a false positive will be of the order of $\left(\frac{N}{\frac{N+1}{2}}\right) p_{th}^{\frac{N+1}{2}}$ and the probability of detecting a false negative will be of the order of $1 - \left(\frac{N}{\frac{N+1}{2}}\right) \bar{\eta}^{\frac{N+1}{2}}$.

By way of an example, for N = 3, the probability of counting a detection with the majority of qubits when an incident photon is transmitted to the detector is $3\eta^2(1-\eta)+\eta^3$, i.e., $1-3\overline{\eta}^2$ when η tends toward 1, as opposed to η^3 for a detection with all the qubits, that is $1-3\overline{\eta}$ when η tends toward 1. Detection with the majority of qubits therefore significantly improves the efficiency of the detection device.

Still for N = 3, the probability of counting a detection with the majority of qubits when no incident photon is transmitted to the detector is $3{p_{th}}^2(1-p_{th})+(1-p_{th})^3$, i.e., $3{p_{th}}^2$ when η tends toward 1, as opposed to ${p_{th}}^3$ for a detection with all the qubits.

The probability of spontaneous excitation p_{th} of a quantum bit is typically of the order of 10^{-3} to 10^{-4}. In practice, it is therefore not necessary to achieve a probability of p_{th}^3 in order to reduce the probability of counting a detection in the absence of an incident photon. A probability of the order of $3p_{th}^2$ offers satisfactory performance. Detection with the majority of qubits therefore maintains good performance in terms of dark noise.

Advantageously, implementing detection with the majority of qubits makes the detection device easier to operate. Indeed, the detection is then more able to withstand spontaneous de-excitation or thermal excitation of an individual quantum bit than when detecting all the quantum bits. Some of the operating constraints of the device that are likely to increase the probability of spontaneous de-excitation can be partially relaxed without impacting the correct operation of the detection device.

Other detection methods can be contemplated. In particular, when not all the quantum bits are identical and some of them offer better performance in terms of dark noise or false negatives, then greater weighting can be placed on these quantum bits than others.

Figure 11 illustrates an embodiment of a device 100' for detecting single microwave photons according to the invention. In this example, the device 100' comprises two quantum bits Q_1, Q_2.

The input resonator R_1 is coupled to the quantum bit Q_1 and the output resonator R_3 is coupled to the quantum bit Q_2. The output resonator R_3 is also used as a reading resonator to read the state of the quantum bit Q_2. The reading resonator 10 allows the state of the quantum bit Q_1 to be read. A bus resonator R_2 connects the quantum bit Q_1 to the quantum bit Q_2.

The presence of an incident photon in the input resonator R_1 and the application of a pump tone 4 to the first quantum bit Q_1 allows the incident photon and the pump tone to be converted into an excitation of the quantum bit Q_1 and an intermediate photon of the bus resonator R_2. Similarly, the presence of an intermediate photon in the bus resonator R_2 and the application of a pump tone 4 to the second quantum bit Q_2 allows the intermediate photon and the pump tone to be converted into an excitation of the quantum bit Q_2 and an output photon of the output resonator R_3.

Reading the state of the quantum bits determines whether or not a detection event should be counted. If the two quantum bits are measured in their excited state, a detection event is counted.

Figures 12 to 17 are graphs illustrating measurements obtained with a device such as the device 100' shown in figure 11.

In this example, the frequency of the probe signal applied to the input of the detection device is 9 GHz. The amplitude of the probe signal and that of the pump tones is fixed. The detection device has an efficiency η of 20 %.

This efficiency is twice as low as that typical of a single quantum bit detection device because of the errors of the two quantum bits that add up.

A pump tone is applied to each of the two quantum bits. The frequencies of the pump tones of the two quantum bits are scanned individually over a frequency interval. For each pair of pump frequencies ($f_{p,1}$, $f_{p,2}$), i.e., ($\omega_1/(2\pi)$, $\omega_2/(2\pi)$), the probability that a signal is actually detected on either one of the quantum bits is measured, on the one hand, when a probe signal is sent to the input resonator and, on the other hand, when no probe signal is sent.

For each of figures 12 to 17, the frequency $f_{p,2}$ of the pump tone of the second quantum bit Q_2 is represented on the abscissa and the frequency $f_{p,1}$ of the pump tone of the first quantum bit Q_1 is represented on the ordinate.

Figure 12 shows the probability of detecting a signal on the first quantum bit Q_1 when a probe signal is actually sent. It can be seen that this probability is high, of the order of 0.25, around a determined frequency $f_{p,1}$, which is the one meeting the condition $f_{p,1} = f_{q,1} + f_{r,2} - f_{r,1}$. The frequencies $f_{q,1}$, $f_{r,1}$ and $f_{r,2}$ are actually constant during the measurement: the four-wave mixing allowing the conversion of the incident photon is therefore only allowed

for this determined frequency $f_{p,1}$. It should be noted that the frequency $f_{p,2}$ of the pump tone of the second quantum bit has no effect on the detection process of the first quantum bit.

Figure 13 shows the probability of detecting a signal on the first quantum bit Q_1 when no probe signal is sent. It can be seen that this probability is uniformly low, of the order of 3.10^{-3}. A slightly higher noise is observed around the frequency $f_{p,1}$ meeting the condition $f_{p,1} = f_{q,1} + f_{r,0} - f_{r,1}$. This is due to false positives of the first quantum bit caused by thermal noise in the input resonator.

Figure 14 shows the probability of detecting a signal on the second quantum bit Q_2 when a probe signal is actually sent. A detection on the second quantum bit Q_2 is only allowed in the presence of a photon in the bus resonator coupling the two quantum bits, i.e., when a detection is performed on the first quantum bit Q_1. Therefore, the high probability zone assumes the form of a spot resulting from an intersection between the line visible in figure 12 and a vertical line corresponding to the frequency $f_{p,2}$ meeting the condition $f_{p,2} = f_{q,2} + f_{r,3} - f_{r,2}$. This zone represents the optimal operating space for the detection device.

Figure 15 shows the probability of detecting a signal on the second quantum bit Q_2 when no probe signal is sent. It can be seen that the noise of the second quantum bit is relatively high and comprises zones where the noise is more pronounced.

Figure 16 shows the probability of detecting a signal both on the first quantum bit Q_1 and on the second quantum bit Q_2 when a probe signal is actually sent. This result corresponds to the frequency space where the four-wave mixing conditions are verified on the two quantum bits.

Figure 17 shows the probability of detecting a signal both on the first quantum bit Q_1 and on the second quantum bit Q_2 when no probe signal is sent. It can be seen that this probability is much lower than that of individually detecting a signal on the first or on the second quantum bit. The zones of relatively higher probability (of the order of 10^{-4}) in the center of the graph are due to the dark noise caused by the residual thermal noise. The zones of relatively lower probability (of the order of 10^{-6}) in the corners of the graph represent the intrinsic noise of the device, that is, the dark noise when the efficiency of the detector is zero.

Figures 18 to 20 show the response of the quantum bits of the same detection device to three different incident photon fluxes over a one-second time interval.

In figure 18, no photon flux is sent to the device.

In figure 19, a flux of 11 photons per second is sent to the device.

In figure 20, a flux of 46 photons per second is sent to the device.

The vertical lines represent the detection events, respectively on the first quantum bit Q_1, on the second quantum bit Q_2 and the simultaneous detection events for the two quantum bits Q_1 and Q_2.

It can be seen that the dark noise is very low when considering the two quantum bits simultaneously (4 false positives are measured per second) compared to the dark noise measured individually on each of the two quantum bits.

Other variants and improvements can be contemplated without otherwise departing from the scope of the invention. In particular, the detection device according to the invention can also comprise means for filtering and/or tuning the resonant frequency of the input resonator and/or of the bus resonators and/or of the output resonator. In particular, as shown in the embodiment of figure 21, the detection device can comprise a SQUID device integrated into the input resonator R_1 so as to allow the frequency of this resonator to be tuned. A SQUID device comprises two Josephson junctions arranged in parallel. By inducing a magnetic field in the SQUID, the inductance of the input resonator R_1 can be adjusted, allowing its frequency to be varied. In order to induce the magnetic field in the SQUID 11, a current is conveyed in the vicinity of the SQUID in a fast flux line, i.e., a transmission line short-circuited to ground by a loop.

Claims

1. A single microwave photon detection device (100; 100'), comprising:

- a multi-state quantum system comprising N qudit(s), with N being greater than or equal to 1, the system being capable of performing, in response to receiving an incident microwave photon, a number X of energy transitions between energy levels distributed between the one or more N qudits that is greater than or equal to 2, with these energy transitions corresponding to respective frequencies f_1, …, f_X;
- a set of resonators (R_1, R_2, …) defining X+1 electromagnetic modes of respective frequencies $f_{M,1}$ to $f_{M,X+1}$;
- a parametric pumping system for applying X pump tones of respective frequencies $f_{p,\,i}$, verifying $f_{M,i} + f_{p,i} = f_i + f_{M,i+1}$, with each integer i ranging from 1 to X, so as to frequency convert, by parametric pumping, the excitation contained in an electromagnetic mode i into an excitation of the electromagnetic mode i+1 and a transition i of the relevant qudit;
- a system for reading the energy levels of the one or more qudits of the quantum system providing information concerning whether or not an incident microwave photon has been received.

2. The detection device as claimed in claim 1, the set of resonators comprising X+1 resonators defining the X+1 electromagnetic modes.

3. The detection device as claimed in any of the preceding claims, the quantum system comprising a qudit on which the X energy transitions occur.

4. The detection device as claimed in claim 1, the quantum system comprising at least two spatially distinct qudits, between which the X energy transitions are distributed.

5. The detection device as claimed in claim 4, at least one of the two qudits being a qubit.

6. The detection device as claimed in claim 4, the two qudits being qubits.

7. The detection device as claimed in claim 4, at least one of the two qudits having at least three energy levels.

8. The detection device as claimed in claim 1 or 2, the quantum system comprising a qubit on which one of the energy transitions occurs and a qudit with at least three levels on which at least one other energy transition occurs.

9. The detection device as claimed in any of the preceding claims, the one or more qudits being transmon type superconducting qudits.

10. The detection device as claimed in any one of the preceding claims, the reading system measuring the state of each qudit.

11. The detection device as claimed in any one of the preceding claims, the reading system comprising at least one reading resonator, the one or more reading resonators being coupled to one or more of the corresponding qudits.

12. The detection device as claimed in any one of the preceding claims, comprising at least as many reading resonators as qudits.

13. The detection device as claimed in any one of the preceding claims, the system comprising an input resonator coupled to a source of microwave photons and an output resonator coupled to a dissipative environment adapted to dissipate a microwave photon.

14. The device as claimed in the preceding claim, the input resonator comprising a SQUID device (11) configured to tune the frequency of the input resonator.

15. A method for detecting an incident single microwave photon using a microwave photon detection device, notably as claimed in any of the preceding claims, the device comprising a multi-state quantum system comprising N qudit(s), with N being greater than or equal to 1, the system being capable of performing, in response to receiving an incident microwave photon, a number X of energy transitions between energy levels distributed between the one or more N qudits that is greater than or equal to 2, with these energy transitions corresponding to respective frequencies f_1, …, f_X, the method comprising the following steps of:

a/ applying X pump tones of respective frequencies $f_{p,i}$, verifying $f_{M,i} + f_{p,i} = f_i + f_{M,i+1}$, with each integer i ranging from 1 to X, so as to frequency convert, by parametric pumping, the excitation contained in an electromagnetic mode i into an excitation of the electromagnetic mode i+1 and a transition i of the relevant qudit;

b/ reading the energy levels of the one or more qudits of the quantum system and deducing information therefrom concerning whether or not an incident microwave photon has been received by the detector.

16. The detection method as claimed in the preceding claim, at least one of the energy transitions being a transition of a qubit from a ground state to an excited state.

17. The detection method as claimed in any of claims 15 or 16, at least one of the energy transitions being a transition of a qudit from a ground state to an excited state or between two successive excited states.

18. The detection method as claimed in claim 16, each energy transition being a transition of a qudit between two successive energy states.

19. The detection method as claimed in any of claims 15 to 18, the step of reading the energy levels of the one or more qudits involving detecting whether a majority of energy transitions have occurred in the quantum system.

20. The method as claimed in the preceding claim, the quantum system comprising an odd number X of energy transitions.

21. The detection method as claimed in any of claims 15 to 18, the step of reading the states of the one or more qudits involving detecting whether the X energy transitions have actually occurred.

22. The detection method as claimed in any of claims 15 to 21, comprising, prior to step a/, a step of adjusting the passband of the quantum system in which the amplitude A_i of the frequencies of the pump tones is determined so as to adjust said passband to a desired value.

23. A device (100, 100') for detecting a single microwave photon (2) comprising:

- a number N of quantum bits (Q_1, …, Q_N) that is greater than or equal to 2 with two energy levels whose ground state and an excited state are controllable and detectable, the transition between the ground and excited states of each quantum bit Q_i having a frequency $f_{q,i}$ for i ranging between 1 and N inclusive;
- an input resonator (R_1) configured to receive an incident single microwave photon (2) and having a frequency $f_{r,1}$, the input resonator being coupled to a first quantum bit Q_1 of the N quantum bits;
- an output resonator (R_{N+1}) configured to discharge an output photon (3) and having a frequency $f_{r,N+1}$, the output resonator being coupled to an N-th quantum bit Q_N of the N quantum bits;

- a number (N-1) of bus resonators R_j configured to transmit an intermediate photon from the quantum bit Q_{j-1} to the quantum bit Q_j and each having a frequency $f_{r,j}$, for j ranging between 2 and N inclusive;
- at least one reading system (10) coupled to the N quantum bits so as to detect their energy levels, notably N or less than N reading systems;
- at least one parametric pumping transmission line (20), notably N or less than N transmission lines, configured to transmit a pump tone to one of the N quantum bits and/or to one of the input, output or bus resonators, so that a photon of an input or bus resonator R_i and a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} – f_{r,i}$ can be converted into an excitation of the quantum bit Q_i and a photon of the bus or output resonator R_{i+1}, for i ranging between 1 and N inclusive.

24. The device as claimed in claim 23, comprising a number N of reading systems (10), each coupled to one of the N quantum bits, for detecting the state of the quantum bit.

25. The device as claimed in any of claims 23 and 24, comprising a number N of parametric pumping transmission lines (20) each configured to transmit a pump tone to one of the N quantum bits and/or to one of the input, output or bus resonators, so that a photon of an input or bus resonator R_i and a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} – f_{r,i}$ can be converted into an excitation of the quantum bit Q_i and a photon of the bus or output resonator R_{i+1}, for i ranging between 1 and N inclusive.

26. A device (100, 100’) for detecting a single microwave photon (2) comprising:

- a number N of quantum bits (Q_1, …, Q_N) that is greater than or equal to 2 with two energy levels whose ground state and an excited state are controllable and detectable, the transition between the ground and excited states of each quantum bit Q_i having a frequency $f_{q,i}$ for i ranging between 1 and N inclusive;
- an input resonator (R_1) configured to receive an incident single microwave photon (2) and having a frequency $f_{r,1}$, the input resonator being coupled to a first quantum bit Q_1 of the N quantum bits;
- an output resonator (R_{N+1}) configured to discharge an output photon (3) and having a frequency $f_{r,N+1}$, the output resonator being coupled to an N-th quantum bit Q_N of the N quantum bits;

- a number (N-1) of bus resonators R_j configured to transmit an intermediate photon from the quantum bit Q_{j-1} to the quantum bit Q_j and each having a frequency $f_{r,j}$, for j ranging between 2 and N inclusive;

- a number N of reading systems (10), each coupled to one of the N quantum bits, for detecting the state of said quantum bit;

- a number N of parametric pumping transmission lines (20) each configured to transmit a pump tone to one of the N quantum bits and/or to one of the input, output or bus resonators, so that a photon of an input or bus resonator R_i and a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} – f_{r,i}$ can be converted into an excitation of the quantum bit Q_i and a photon of the bus or output resonator R_{i+1}, for i ranging between 1 and N inclusive.

27. The detection device as claimed in claim 26, the N quantum bits being transmon type superconducting quantum bits.

28. The detection device as claimed in any of claims 26 and 27, each reading system comprising a resonator.

29. The detection device as claimed in any of claims 26 to 28, the reading system coupled to the N-th quantum bit Q_N comprising the output resonator R_{N+1}.

30. The detection device as claimed in any of claims 26 to 29, the input resonator, the output resonator and the bus resonators being superconducting microwave resonators.

31. The detection device as claimed in any of claims 26 to 30, the input resonator being coupled to a source of microwave photons and the output resonator being coupled to a dissipative environment adapted to dissipate a microwave photon.

32. The detection device as claimed in any of claims 26 to 31, the input resonator comprising a SQUID device (11) configured to tune the frequency of the input resonator.

33. A method for detecting a single microwave photon implemented by means of a detection device (100, 100’) as claimed in any of claims 26 to 32, comprising the steps of:

a/ applying a pump tone of frequency $f_{p,i} = f_{q,i} + f_{r,i+1} – f_{r,i}$, to each quantum bit Q_i, for i ranging between 1 and N inclusive;

b/ measuring the state of each quantum bit Q_i.

34. The detection method as claimed in claim 33, the detection device comprising an odd number of quantum bits, the method comprising, after step b/, a detection

step c/ involving determining whether at least a majority (N+1)/2 of the quantum bits is measured in the excited state, in which case a detection event is counted.

35. The detection method as claimed in claim 33, the method comprising, after step b/, a detection step c1/ involving determining whether all the quantum bits are measured in the excited state, in which case a detection event is counted.

36. The detection method as claimed in any of claims 33 to 35, comprising, prior to step a/, a step a0/ of adjusting the passband of the detection device in which the amplitude A_i of the pump tones of frequency $f_{p,i}$ is determined so as to adjust said passband to a desired value.