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(54) Title: LOW NOISE AMPLIFIER

(57) Abstract: The present invention relates generally to the field of quantum limited amplification at microwave frequencies. Quantum limited amplification at microwave frequencies is furthermore particularly important with respect to superconducting qubits and nanoelectromechanical systems. Described herein are a plurality of low noise amplifiers. The amplifiers described herein generally comprise at least one Josephson junction and utilize negative differential resistance of the junction or junctions. Furthermore, embodiments describe shunted single junction amplifiers which provide a self-organized noise compression mode.

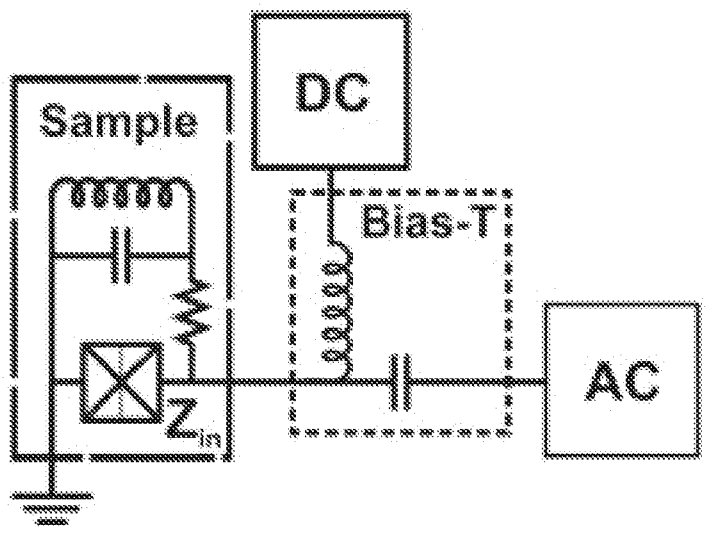


Fig. 1

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LOW NOISE AMPLIFIER

FIELD OF INVENTION

The present invention relates generally to the field of quantum limited amplification at microwave frequencies. Quantum limited amplification at microwave frequencies is furthermore particularly important with respect to superconducting qubits and nanoelectromechanical systems.

BACKGROUND OF THE INVENTION

Achieving quantum limited amplification at microwave frequencies has become increasingly important. Particularly, such amplification has become important for superconducting qubits and nanoelectromechanical systems. Low noise temperatures with respect to the quantum noise have been achieved using several types of amplifiers. However, inadequacies in each of the previous amplifiers require a novel solution in the field.

The lowest noise temperatures, with respect to the quantum noise, have been achieved using nondegenerate parametric amplifiers based on superconducting quantum interference devices (SQUIDs). These devices yield a noise temperature T_n of about (1.0-1.6) T_q, where T_q is the fundamental noise limit of a phase-preserving amplifier at frequency $\omega/2\pi$, otherwise defined as the standard quantum limit $T_q = \hbar\,\omega/2k_B$.

Other implementations of near-quantum limited amplification have been realized by means of Josephson ring oscillators, DC-SQUIDs and parametric amplifiers based on Josephson junction arrays. Devices based on photon-assisted tunneling SIS-mixers have also been used and yield noise temperatures of $T_n = 1.2T_q$. However, these devices lack power gain, but they do have a large gain in photon number due to conversion from high to low frequency.

Negative differential resistance devices, in particular tunnel diodes, have been used to construct oscillators and amplifiers for microwave frequencies. These devices are capable of very fast operation. Furthermore, they were among the first to be used at microwave

frequencies because they display little or no excess noise in the negative resistance bias region. What is needed in the art is an amplifier based on the negative resistance which has near quantum-limited operation.

SUMMARY OF THE INVENTION

It is an aspect of the present invention to provide an amplifier based on the negative resistance of a selectively damped Josephson junction.

Selective damping and negative resistance are applied in the embodiments of the invention to provide mechanisms of gain and mechanisms and solutions for lowering the equivalent input noise of the amplifier. Furthermore, it is an aspect of embodiments of the present invention to provide an amplifier with quantum-limited or near-quantum-limited noise performance. Such aspect is achieved in certain embodiments by mixing the quantum noise from the Josephson oscillation regime down to the signal frequency.

Still further, it is an aspect of certain embodiments of the present invention to provide a negative-resistance amplifier based on an unshunted, single Josephson junction (JJ). In certain embodiments, said amplifier is provided operating in a noise compression mode.

According to certain embodiments of the present invention there is described herein a low noise amplifier comprising at least one Josephson junction, a damping circuit in parallel to the at least one Josephson junction, wherein the Josephson junction is undamped in a signal band, and an external circuit connected in parallel to the Josephson junction.

Additionally, there are described herein embodiments of a low noise amplifier wherein the signal band is in between 0Hz and the Josephson frequency of the Josephson junction. Furthermore, there are described herein embodiments of a low noise amplifier wherein outside the signal band the damping circuit impedance is resistance R, a series low-pass or bandstop filter defining signal band is connected to the parallel resistor R to ensure undamping of the Josephson junction in the signal band, and the dynamic impedance of the parallel connection of the Josephson junction and the damping circuit is Z(f) with a negative real part.

Still further, there are described herein embodiments where there is a a low noise amplifier comprising two or more Josephson junctions in parallel, a damping circuit or damping circuits in parallel to the Josephson junctions, wherein the Josephson junctions are undamped in a signal band, and an external circuit connected in parallel to the Josephson junctions.

It is an aspect of certain embodiments of the present invention that there is provided an amplifier using unshunted Josephson devices having a modified impedance environment.

Unshunted junctions are attractive as low-noise devices since they minimize fluctuations by avoiding unnecessary dissipation in the junction environment. In voltage-biased (V_b) operation, these devices can be considered as mixers between the signal frequency (ω_s around a few GHz, for example, in the range of 1-10 Ghz) and the Josephson frequency ($\omega_j = (2e/\hbar)\ V_b = 2\pi \times 10 - 300$ GHz) including sidebands. A frequency-dependent environmental impedance can be employed for controlling mixing strengths, as the Josephson junction is a phase driven current generator, and the impedance makes the conversion between these two quantities.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a principal scheme of a single junction amplifier

Figure 2a shows a circuit object realizing negative dynamic resistance within a single band determined by the filter.

Figure 2b shows the object of fig. 2a with a simple realization of the filter.

Figure 2c shows the object of fig. 2b stabilized by an external impedance Z_0.

Figure 3 shows a graph of the input noise temperature T_n vs. maximum gain of an SJA.

Figure 4 shows a circuit which is both stabilized and which can be operated as a reflection amplifier.

Figure 5 shows a generalization of a circuit similar to fig. 2 which is in a SQUID configuration.

Figure 6 shows an arrangement utilizing an object similar to fig. 4 directly as a microwave amplifier.

Figure 7 shows a circuit where the source to be measured with impedance Z_S connected in parallel to a Josephson junction and a second stage amplifier.

Figure 8 shows a circuit where the source to be measured Z_S is connected in series with a Josephson junction and a second stage amplifier which is further operated in an actively feedbacked mode to lower its impedance and to provide active voltage bias to Z_S and the Josephson junction with its shunting circuit.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

According to an embodiment of the present invention, there is described herein a single junction amplifier (SJA) having a Josephson junction (JJ). The fundamental macroscopic principle of the SJA is that the intrinsic resistance of a JJ is negative over time scales much longer than $1/\omega_J$.

The intrinsic resistance is usually hidden in weakly damped JJs since the negative-resistance branch is unstable. On the other hand, for strongly damped junctions, the total dynamic resistance is positive. This can be seen from the current-voltage *IV* characteristics $v_b = \sqrt{i_b^2 - 1}$ for a Josephson junction with negligible capacitance (valid for i_b>1). Here $v_b = V_b/I_cR$ denotes the voltage scaled with critical current I_c and the shunt resistance R while $i_b = I_b/I_c$ is the dimensionless current. Solving for the current through the junction alone, $i_{JJ} = i_b - v_b$, we get for the scaled dynamic resistance $r_d = \frac{R_d}{R} = \frac{1}{di_{jj}/dv_b} = \frac{1}{di_b/dv_b - 1}$

This yields $\sqrt{v_b^2+1}/\left(v_b - \sqrt{v_b^2+1}\right)$ negative at all bias points.

A schematic of a basic SJA configuration is illustrated in fig. 1. In order to utilize the negative resistance of a JJ for amplification, stable operation should be maintained by sufficient damping at all frequencies. The frequency-dependent damping is set in such a way that the external shunt damps the low frequency dynamics, i.e. $\omega < \omega_s$, where ω_s is the signal frequency, as well as high frequency dynamics, i.e. $\omega > \omega_s$. This ensures both stable DC bias and overdamped Josephson dynamics.

In practice, the separation can be achieved by mounting a shunt resistor in series with a bandstop or low-pass filter. The bandstop filter preferably has a center frequency which is at, or near, the signal frequency, ω_s. The shunt capacitor should be chosen so that it is large enough that it acts as a short at the Josephson frequency to ensure the high frequency dynamics and the IV curve are not modified.

Stabilization in the stop band can be provided by a postamplification circuit. The shunt circuit and the postamplification circuit together guarantee the stability of the device by generating a wide-band resistive environment for the JJ.

Operated as a reflection amplifier, the power gain $|S_{11}(\omega)|^2 = |\Gamma(\omega)|^2$ is determined by the reflection coefficient $\Gamma(\omega) = (Z_{in}(\omega) - Z_0)/(Z_{in}(\omega) + Z_0)$ where $Z_{in}(\omega)$ is the impedance of the JJ, the shunt and the series inductance; Z_0 is the impedance of the readout circuit. From the equation, it can be seen that there is gain, i.e. $S_{11} > 0$ dB, at all values of negative resistance. Additionally, there is a strong divergence around $Z_{in} = -Z_0$.

The negative real part of the impedance can be utilized by connecting the Junction in parallel with impedance Zs. For example, if $Z_{in}(\omega)$ is real and negative, and Zs is real and positive, the parallel connected impedance $(Z_{in}(\omega)Zs)/(Z_{in}(\omega) + Zs)$ is real, very large and positive if Zs is slightly larger than $|Z_{in}(\omega)|$. When the parallel connection is driven by a signal current this leads to large voltage enhancement. An example schematic according to the present embodiment is shown in fig. 7.

Furthermore, it is possible to connect Zs in series with $Z_{in}(\omega)$. Similarly, with Zs real and slightly larger than $|Z_{in}(\omega)|$ assumed real and negative there is a very small positive real total impedance $Zs + Z_{in}(\omega)$ enhancing current as the series connection is biased with signal voltage. This can be utilized, for example, together with an actively stabilized circuit. An example schematic according to the present embodiment is shown in fig. 8. In accordance with the present embodiment there is provided a voltage bias with required small-impedance second-stage amplifier at the same time.

In the stopband of the shunt circuit, the input impedance $Z_{in}(\omega_s)$ may consist, comprise substantially of or merely consist of the JJ, which is real and negative. According to certain

embodiments, there can also be an impedance transformer. The impedance transformer can be located between the junction and external circuit formed, for example, by a reactive element in series with the Josephson junction. Some examples of reactive elements are inductance, capacitance or a series connection of inductance and capacitance. For $|R_d| \gtrsim Z_0$, large gain with stable operation can be obtained. The impedance transforming circuit is useful for operating conditions where $|R_d| \gg Z_0$ and it is desired to change the reference level impedance Z_0. For example, an impedance transforming circuit can be used to transform impedance from 50 Ω, e.g. typical for standard RF technology, to a level of, for example 1 kΩ, e.g. which is a typical value of $|R_d|$ for small Josephson junctions at high bias voltages.

At frequencies sufficiently below the characteristic frequencies of the Josephson junction, e.g. plasma frequency $f_p = ((1/2\pi \Phi_0)(I_o/C))^{1/2}$ and the Josephson frequency $f_J = V/\Phi_0$, the Josephson junction is described by a negative dynamic resistance ($R_d = dV/dI < 0$). Stable operation enabling biasing at a finite voltage requires damping of the dynamics as discussed above. This can be realized, for example, by a resistor R in parallel to the junction.

According to an embodiment of the invention, the damping from a frequency band is removed. The removed frequency band, herein referred to as the signal band, is removed by setting a bandstop filter in series with R. Within the signal band, the object formed in this way can be electrically described as impedance $Z(f)$, which is formed by a negative resistance R_d and the reactive components from the filter. This is shown in fig. 2a. A parallel connection of L and C in such a way that $f_0 = 1/2\pi(LC)^{1/2}$ is equal to the center frequency of the signal band is shown in fig. 2b. This example of a filter is merely a simple realization of the filter. However, other, more complex filters can be used in its place without departing from the scope of the present invention.

An object formed according to such an embodiment tends to oscillate at a frequency determined by the reactive components of the filter circuit. Additionally, the reactive components of a circuit to which the object is connected can also determine the oscillation frequency of the object. Stability can be restored if the object is connected to an external circuit, said external circuit described by impedance $Z_2(f)$ in the signal band such that the

real part of the impedance of the parallel connection of the object $Z(f)$ and the external circuit together is positive at all frequencies.

For example, for the realization of the object shown in fig. 2b, such circuit is one corresponding to real impedance $Z_2(f) = Z_0$ such that $Z_0 < |R_d|$ as shown in fig. 2c. Fig. 4 shows an example of stabilising an SJA object, such as shown in fig. 1 or fig. 2a-c, by external impedance Z_0 while at the same time enabling operation as a reflection amplifier.

The dynamics of Josephson junction circuits can be analyzed using a Langevin type of differential equation for the phase variable φ across the Josephson junctions. In the semiclassical approach, the generalized Nyquist noise formula by Callen and Welton with the frequency dependence $0.5\hbar\omega \coth(\hbar\omega/2K_BT)$ is employed as the colored noise source in the differential equation.

At the Josephson frequency, the semiclassical noise power per unit bandwidth is so large ($\propto \hbar\omega_J \gg k_BT$) that, after downmixing, it will have observable effects on the phase dynamics at the signal frequency ω_s. Since the noise at ω_s is cut off from the Josephson junction by the bandstop filter as shown in fig. 1, direct noise from the shunt is avoided and only the down-mixed noise is present in the SJA. The absence of direct noise ensures good noise characteristics for our SJA. This feature is a noticeable advantage over SJAs with traditional microwave SQUID amplifiers.

An amplifier constructed according to the present invention can be used as an ultra-low noise amplifier near or at the so called standard quantum limit which is the fundamental limit of all phase-preserving amplifiers. So called effect of noise compression, observed experimentally and theoretically, can be utilised to improve the noise properties of the amplifier.

The first example utilizing an SJA according to an embodiment of the present invention has the following parameters: Z_0 is the impedance of the source and the readout circuit; R,C and L are the shunt resistance, capacitance and inductance respectively; I_c, C_J, ω_p and β_c are the critical current, the capacitance, plasma frequency and the Stewart-McCumber parameter of the junction respectively; C_2 and L_2 are the capacitance and the inductance in

series with the SJA device, i.e. the impedance transformer; ω_s is the signal frequency and; I_b and ω_J are the bias current and the Josephson frequency at the optimal operating point respectively.

A first experiment was carried out in accordance with the first example. In the experiment, $Z_0 = 50\Omega$, $R = 4\Omega$, $C = 4.26$pF, $L = 702$ pH, $C_2 = 33$ pF, $L_2 = 14.25$ nH, $\omega_s = 2.865$ GHz, $I_c = 17$ μA, $C_J = 0.35$ pF, $\omega_p/(2\pi) = 61$ GHz, $\beta_c = 0.29$, $I_b = 140$ μA and $\omega_J/(2\pi) = 270$ GHz.

In the experiment the gain vs. frequency was recorded at several power levels. The maximum measured gain of the SJA was found to be 28.3 ± 0.2 dB. The 21 dB compression point for P_{in} was found to be around -134 dBm. This yields a dynamic range of 70 dB as the input noise corresponds to -204 dBm. For the -3 dB bandwidth, we obtain BW approximately equal to 1 MHz.

Further details concerning the present example can be found in U.S. Provisional application 61/452,664 filed March 15, 2011 which is herein incorporated by reference in its entirety. Specifically, more details concerning the results of the experiment can be found in figure 3 of the provisional application.

The experiment shows significant improvement of the signal to noise ratio when the SJA is switched on and operated at its maximum gain. Based on this improvement, we find that the input-referred noise power added by the amplifier is 220 ± 70 mK where $0.5\hbar\omega/k_B \coth(\hbar\omega/2k_BT) = 90$ mK originating from the source has been subtracted. This corresponds to $T_n \approx (3.2 \pm 1.0)\, T_q$. It was found that the best noise temperature can be obtained at the largest gain of the SJA.

Further to the experiment according to the first example was a theoretical analysis of the same device. To theoretically model a single junction device with arbitrary, frequency-dependent environment with $0 < \beta_c = 2eR^2(\omega)I_cC_J/\hbar <, 1$, we simulate numerically the electrical circuit on the basis of the DC and AC Josephson relations which define a nonlinear circuit element having the properties: $I_J = I_c \sin\varphi$ and $V = (\hbar/2e)\, \partial\varphi/\partial t$.

The numerical simulations have been compared with analytic methods using an approximate model where we have adapted the resistively and capacitively shunted

junction (RCSJ) approach to the modified environmental impedance of the SJA. The numerical and analytic models take into account the Callen and Welton quantum noise from the environment semiclassically.

Down-conversion of the noise at ω_J is the main quantity which is to be minimized for optimum performance. The theoretical gain curve is seen to follow the experimental behavior closely and it yields 42 MHz for the gainbandwidth product. The simulated maximum gain amounts to 28.9 ± 0.5 dB. All these findings are in excellent agreement with the experimental data.

Basically, the shape of the gain curve indicates that the amplification mechanism is based on mixing between ω_s and the sidebands of ω_J. This occurs along with the conversion from down-mixed currents at ω_s to voltage by the shunt impedance. For comparison, we have also calculated a linearized response curve where the Josephson junction has been replaced by a negative resistance of R_d = -1370 Ω from Eq. (1).

The numerical simulations yield T_n= 270 ± 30 mK which is close to the experimentally found T_n= 220 ± 70 mK. Hot-electron effects were taken into account by using an applicable model, on the basis of which the electronic temperature in the shunt was estimated to be $Te \approx 400$ mK instead of the base temperature 70 mK.

The noise temperature is not particularly sensitive to hot electron effects when the shunt is fully blocked by the LC resonator at the center frequency. However, when going away from the center frequency, direct noise may leak out from the shunt reducing the useful band to ''a noise-temperature-limited'' range.

For the noise analysis, we define a noise process $\varphi_s(t)$, band-limited near the signal frequency. Another noise process φj(t) with $\langle \varphi_j(t)^2 \rangle \ll 1$ covers the Josephson frequency and one pair of sidebands ($\omega_J \pm \omega_s$). φ_j has a small variance because of the low impedance of the junction capacitor at high Josephson frequency.

We expand $i_J = \sin \varphi(t) \approx \sin(\omega_J t + \varphi_s + \varphi_j)$ in order to describe the junction as a DC current generator plus two AC current noise generators: one at ω_s and the other around the

Josephson frequency. In the Fourier plane, the AC Josephson relation and the impedance environments at low and high frequencies establish the down-mixing noise process.

We denote the variance of the phase noise over the signal band by $\delta_s^2 = \langle \emptyset_s(t)^2 \rangle$. In our calculations, we expand $\exp(i\varphi_s) \approx J_0(r) + i(2J_1(r)/r)\varphi_s$. This gives a good approximation at small δ_s^2 but breaks down when additional sidebands, such as $\omega_J \pm \omega_s$ and so on, become significant. These Bessel functions of the first kind have the phase noise amplitude r divided by the signal band. Ideally, r should follow the Rayleigh distribution.

In our analysis, we treat separately the limit of small fluctuations, $\delta_s^2 \ll 1$ and the regime with $\delta_s^2 \geq 1$, in which noise compression effects appear. With large gain and resonantly boosted current-voltage conversion, the phase fluctuations will grow so much that the non-linearities begin to limit the gain. At this point the system is driven to a steady state where the downmixing process becomes altered and significantly suppressed.

The number of added quanta per unit band from mixed-down noise is derived in the Supplementary material: $\frac{k_B T_{mix}}{\hbar \omega_s} = \frac{N\xi(\delta_s^2)}{2}\left(\frac{1+\beta_c^2 v_b^2}{1+3\beta_c^2 v_b^2}\right)\left(\frac{G_m-1}{G_m}\right)$ [eq.1] where $N = \omega_J/\omega_s$ and the factor $\left(\frac{G_m-1}{G_m}\right)$ can be neglected at large gain. Noise suppression is denoted by the compression factor $\xi(\delta_s^2) \leq 1$ which equals unity at $(\delta_s^2) \ll 1$ and decreases towards zero with growing variance.

In our model with the sidebands $\omega_J \pm \omega_s$, we obtain $\xi(\delta_s^2) = < J_0^2(r) > \sim exp(-\delta_s^2)$. Hence, large improvement in noise performance can be achieved compared to the linear where $\xi(\delta_s^2) = 1$.

The role of noise compression in the operation of the SJA can be seen by plotting the uncompressed noise from Eq. (1) multiplied by the simulated gain. The output noise temperature from the actual simulation differs from it, which is an indication of noise compression. The simulated spectrum is rounded near the gain peak, which creates a dip in the input noise temperature.

In fig. 3, the input noise temperature at G_m is plotted as a function of the gain. Linear theories predict convergence towards T_n = 2.4 K at $G_m \gg 1$. This can be derived from Eq. (1) by taking $\xi = 1$. Above a threshold gain of ~ 13 dB, noise suppression sets in. From the analytic model with two sidebands $\omega_J \pm \omega_s$, we obtain $\xi = < J_0^2(r) \geq 0.44$ for the compression factor at G_m = 28 dB and the noise temperature reduces to T_n = 1.0 K. Compared with numerical simulations, the analytic model yields nearly 3–4 times larger value for T_n.

According to an embodiment of the present invention, an SJA object as shown in fig. 1 or fig. 2a-c can be modified to include a parallel connection of two Josephson junctions in a SQUID configuration. An example of the present embodiment is shown in fig. 5. A configuration such as that shown can be used to effectively tune the critical current of the system. Such configurations can also be used to provide an additional signal input in the form of a magnetic flux.

Having a circuit similar to fig. 4 embeded in a SQUID configuration makes it possible to modulate the signal detected by the second stage amplifier by the magnetic flux driven to the flux tuning coil at a frequency smaller than the signal frequency. In this way the system can provide detection and amplification of the flux modulating signal as well.

A SQUID configuration can be used without the additional signal source by driving the flux modulating signal at the signal frequency as in fig. 6. In such a configuration the system can directly provide gain from the flux modulating microwave signal into the second stage amplifier. This arrangement enables, for example, the utilisation of above mentioned noise compression properties with a simpler circuit arrangement as that of fig. 4.

The compression mechanism for noise is crucial for the high bias operation of an SJA as otherwise T_n would grow directly proportional to ν_b (N in Eq. (1)). The operation with noise compression can be viewed as self-organization of the system. The objects described herein and embodiments thereof are the first Josephson junction amplifiers in which noise and the impedance of the environment are employed to determine the working point of the device in a self-organizing way. The self-organization brings the system into large

fluctuation operation, where conventional linear treatments break down and the noise characteristics become better than derived from such theories.

Microscopic degrees of freedom give rise to a macroscopic order. This can be parameterized to describe the behavior of the system. According to certain embodiments of the present invention, the macroscopic ordering is dictated by the integrated noise over the amplified bandwidth. This parameter governs the macroscopic characteristics of the device. For example, the effective critical current and the gain of the device for external signals. The actual value of the gain is set by the higher order terms present in the Josephson energy, which resembles that of the order parameter stabilization in regular phase transitions.

The bandwidth of an SJA is fundamentally limited below the Josephson and plasma frequencies, 0.5 $\min(\omega_J, \omega_p)$. It can be shown that the gain-bandwidth product is $|\Gamma|_{max} \times BW = 2/|R_d|(C + C_J)$ in our first-order filtering scheme. In the measured amplifier, the capacitance of the bandstop filter is $C \approx 4.3$ pF and $C_J = 0.35$ pF. Furthermore, using $R_d = -1370\ \Omega$ as in our operating point of interest, the formula yields $|\Gamma|_{max} \times BW = 50$ MHz while ≈ 40 MHz is obtained experimentally.

In general, stability of the amplifier requires that $C > C_J$. Reduction of the shunt capacitance facilitates improvement of the gainbandwidth product but the boundary condition $R>>(\omega_J C)^{-1}$ must be met. High bandwidth is predicted at small R_d too, which can be obtained most effectively by increasing the critical current. Additionally, C_J controls the value of R_d so that the optimum for gain-bandwidth product is obtained for a small junction with a high critical current density.

According to a further embodiment of the present invention there is herein disclosed another possible low noise regime for an SJA having the limit of small ω_J. In analyzing a few devices at $\nu_b = 3$ ($N = 2.33$) with different β_c it was possible to obtain analytically that the down-mixed noise contribution is around $\hbar\omega$ at $\beta_c = 0.3 - 0.5$ without any noise compression. This was verified in numerical simulations according to which 0.9 ± 0.2 quanta were added by SJA's according to the present invention.

The addition of one quantum indicates that the noise behavior of an SJA is reminiscent to that of heterodyne detection where the image frequency brings an extra noise of 0.5 $\hbar\omega$ to the detected signal. In other words, both sidebands of the Josephson frequency add 0.5 $\hbar\omega$ to the noise temperature.

The present invention should not be limited to the explicit embodiments and examples provided herein. The embodiments and examples are merely described to help illustrate the underlying invention. Variations and extensions of the explicit embodiments and examples will be apparent to those of ordinary skill in the art without departing from the scope of the present application. For example, using numerical simulations, it is possible to produce the measured noise temperature $3.2T_q$ at high bias. Such simulations show signs for the complex behavior of SJA's according to the present invention.

The analytical model mixes down noise only from two sidebands $\omega_J \pm \omega_s$. The consideration of which is sufficient at low Josephson frequency and small phase noise variance δ_s^2. Consequently, the predictions of $T_n \sim \hbar\omega$ from our analytical modeling are reliable at low bias voltage. In the noise compression mode, $(\delta_s^2) \geq 1$, our simulations show that the analytic model fails and an extension in the number of tracked sidebands is necessary. Moreover, pronounced noise compression may be able to drive an SJA into the standard quantum limit T_q.

CLAIMS

1. A low noise amplifier comprising;
   - at least one Josephson junction,
   - a damping circuit in parallel to the at least one Josephson junction,
   - wherein the Josephson junction is undamped in a signal band, and
   - an external circuit connected in parallel to the Josephson junction.

2. A low noise amplifier according to claim 1, wherein,
   - the signal band is in between 0Hz and the Josephson frequency.

3. A low noise amplifier according to claim 1, wherein,
   - outside the signal band the damping circuit impedance is resistance R,
   - a series bandstop or lowpass filter defining signal band is connected to the parallel resistor R to ensure undamping of the Josephson junction in the signal band, and
   - the dynamic impedance of the parallel connection of the Josephson junction and the damping circuit is Z(f) with a negative real part.

4. A low noise amplifier according to any of the previous claims, wherein
   - the external circuit in parallel to the Josephson junction and the damping circuit has impedance Z2(f) in the signal band such that the real part of the parallel connection of impedances Z(f) and Z2(f) is positive in the signal band.

5. A low noise amplifier according to any of the previous claims, wherein
   - the external circuit is arranged so that impedance $Z_2(f)$ is formed by a circuit consisting of a circulator or a directional coupler connecting the Josephson junction and the damping circuit across microwave transmission lines to signal source and second stage amplifier enabling operation of the Josephson junction and the damping circuit as reflection amplifier with power gain (| Z2(f)- Z(f)|/ |Z2(f)+ Z(f)|)^2>1 in the signal band

6. A low noise amplifier according to any of claims 1-4, wherein

- external impedance $Z_2(f)$ is formed by a parallel connection of impedance $Z_S(f)$ of the source to be measured and the second stage amplifier with input impedance $Z_{amp}(f)$.

7. A low noise amplifier according to claim 6, wherein
   - $Z(f)$, $Z_S(f)$ and $Z_{amp}(f)$ are such that $Z_{amp}(f)$ is very large, ideally infinite, in the signal band and the parallel connection of $Z_S(f)$ and $Z(f)$ with impedance given as $Z_S(f)Z(f)/(Z_S(f) + Z(f))$, has large positive real part in the signal band to provide large voltage gain and preserve stability.

8. A low noise amplifier according to any of claims 1-4, wherein
   - external impedance $Z_2(f)$ is formed by a series connection of a second stage amplifier with impedance $Z_{amp}(f)$ and a source, said source to be measured as $Z_S(f)$.

9. A low noise amplifier according to claim 8, wherein
   - $Z(f)$, $Z_S(f)$ and $Z_{amp}(f)$ are such that $Z_{amp}(f)$ is very small, ideally zero, and the impedance of the series connection of $Z_S(f)$ and $Z(f)$, given as $Z_S(f) + Z(f)$, has small positive real part in the signal band to provide large current gain and preserve stability.

10. A low noise amplifier according to either claim 8 or 9, wherein
   - the second stage amplifier is an operational amplifier or a differential pair used in an actively feedbacked configuration with feedback impedance Z_{fb} to create low input impedance $Z_{amp}(f)$ and/or to enable active voltage bias for the series connection of the Josephson junction and Z_S.

11. A low noise amplifier according to any of claims 6-10, further comprising,
   - a filter, connected to tthe source impedance and/or second stage amplifier, said filter being capable of preventing frequencies other than signal frequency from entering or exiting Z_S and/or Z_{in}.

12. A low noise amplifier according to any of the previous claims, further comprising at least a second Josephson junction in parallel to said at least one Josephson junction.

13. A low noise amplifier according to claim 12, wherein there is at least one additional damping circuit in parallel to the Josephson junctions.

14. A low noise amplifier according to claim 12, wherein

- outside the signal band the impedance of the damping circuit or the damping circuits is resistance R,
- a series bandstop filter defining signal band is connected to the parallel resistor or resistors R to ensure undamping of the Josephson junctions in the signal band, and
- the dynamic impedance of the parallel connection of the Josephson junctions and the damping circuit or the damping circuits is dynamic impedance Z(f) with a negative real part.

15. A low noise amplifier according to any of claims 12-14, wherein

- the external circuit in parallel to the Josephson junctions and the damping circuit or the damping circuits have impedance $Z_2(f)$ in the signal band such that the real part of the parallel connection of impedances Z(f) and $Z_2(f)$ is positive in the signal band.

16. A low noise amplifier according to any of claims 12-15, wherein

- the input is coupled to the amplifier as the flux in the loop formed by the parallel connection of the at least two Josephson junctions and the output as the signal emitted from the parallel connection of the junctions to the impedance $Z_2(f)$ formed by a microwave transmission line terminated by a second-stage amplifier.

17. A low noise amplifier according to any of the preceding claims, wherein the damping circuit comprises at least one resistor and at least one capacitor.

18. A low noise amplifier according to claim 17, wherein the capacitor of the damping circuit is sufficiently large enough to act as a short at the Josephson frequency.

19. A low noise amplifier according to claim 17 or 18, wherein the capacitance of the capacitor of the damping circuit is greater than the capacitance of the Josephson junction.

20. A low noise amplifier according to any of claims 17-19, wherein the resistor of the damping circuit is connected in series to a bandstop filter.

21. A low noise amplifier according to claim 20, wherein the bandstop filter has a center frequency at the signal frequency.

22. A low noise amplifier according to claim 20, wherein the bandstop filter has a center frequency close to the signal frequency.

23. A low noise amplifier according to any of claims 20-22, wherein the input impedance $Z_{in}(\omega_s)$ of the bandstop consists of the Josephson junction.

24. A low noise amplifier according to any of claims 20-22, wherein the input impedance $Z_{in}(\omega_s)$ of the bandstop is comprised of the Josephson junction and an impedance transformer.

25. A low noise amplifier according to claim 24, wherein the impedance transformer is sufficient to change the reference level impedance to a level close to the negative dynamic resistance of the Josephson junction.

26. A low noise amplifier according to any of the preceding claims, wherein the reference level impedance Z_0 is suitable for standard RF technology, preferably on the order of 50Ω.

27. A low noise amplifier according to any of the preceding claims, wherein the Josephson junction is and/or is effectively, shunted.

28. The use of a low noise amplifier according to any of the preceding claims with high critical current density.

29. The use of a low noise amplifier according to any of the preceding claims in a context of a nanoelectromechanical system.

30. The use of a low noise amplifier according to any of the preceding claims in a context of system of a superconducting qubit or qubits.

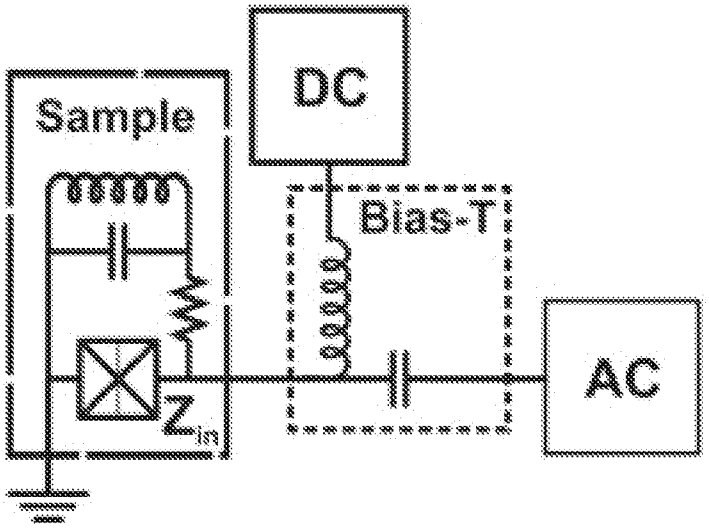


Fig. 1

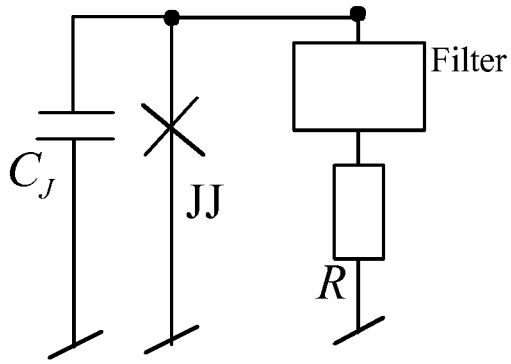


Fig. 2a

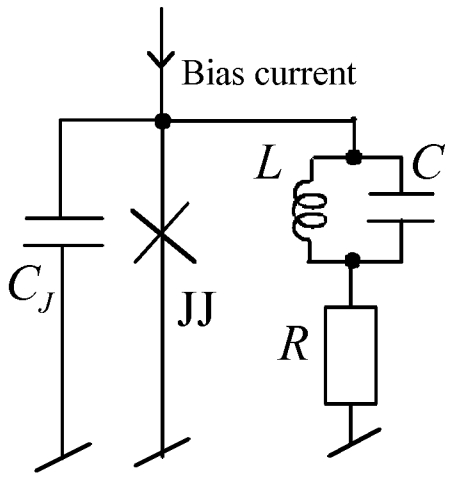


Fig. 2b

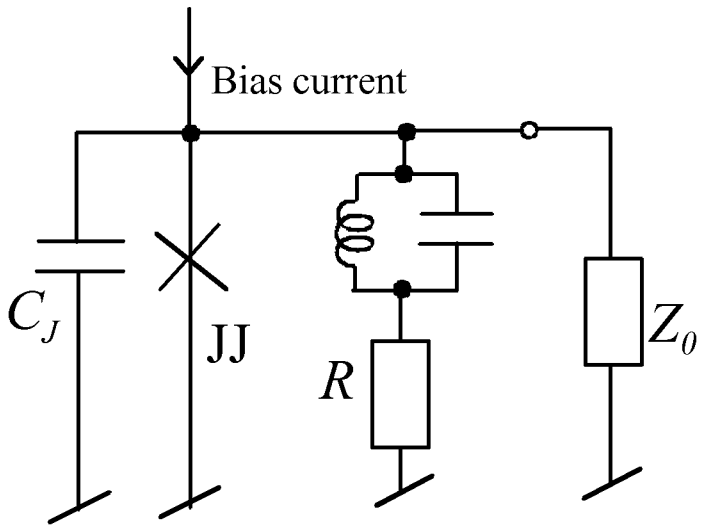


Fig. 2c

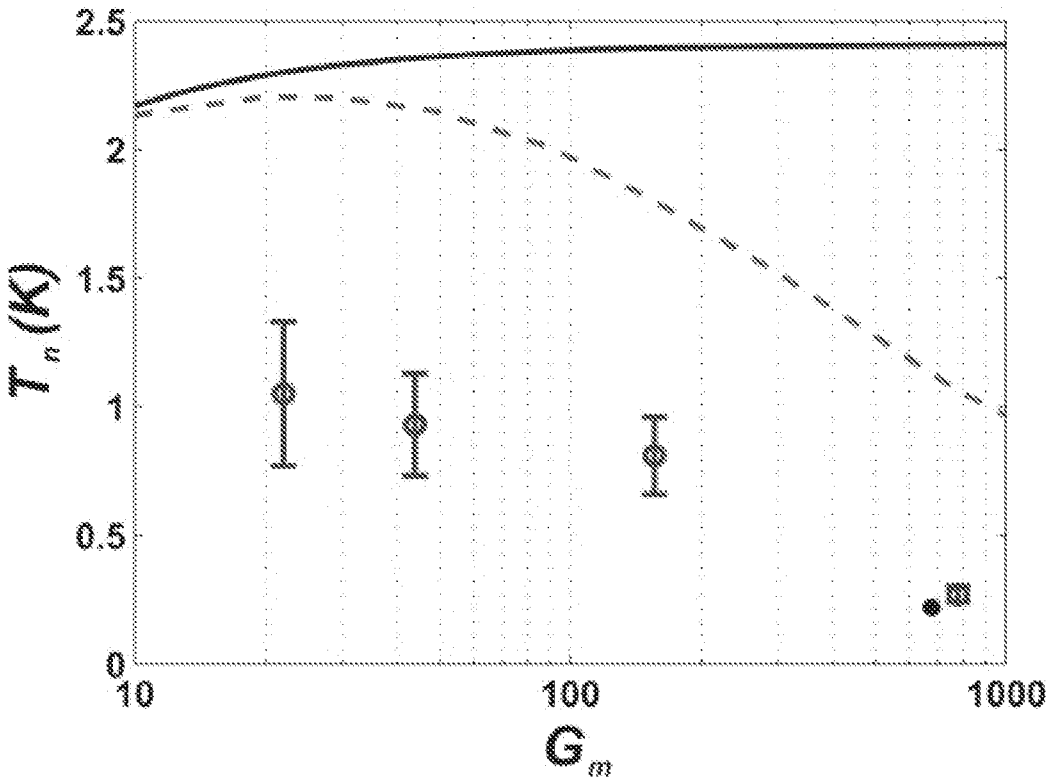


Fig. 3

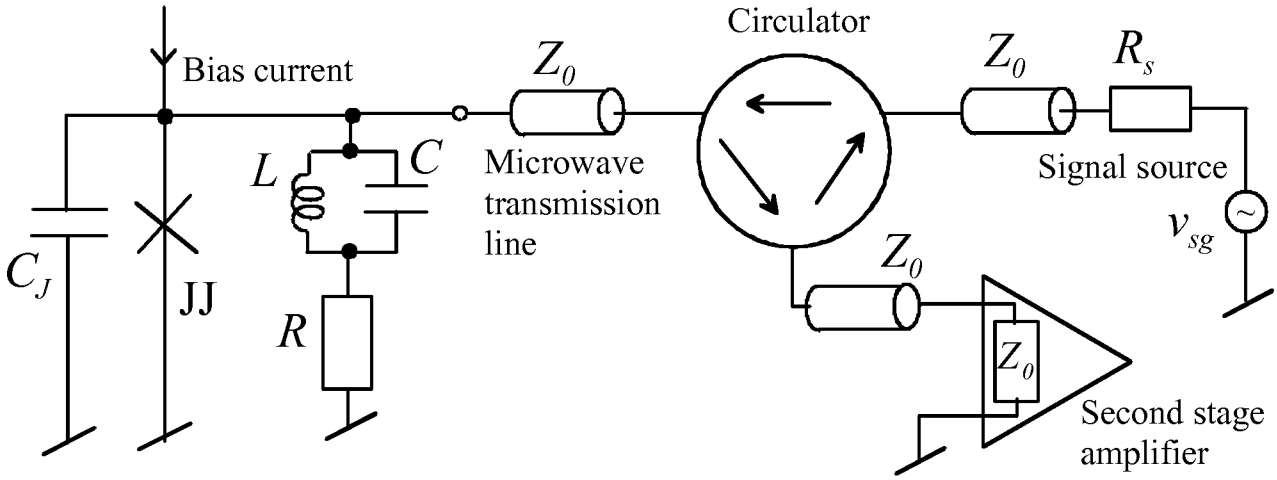

Bias current
Z_0
Circulator
Z_0
R_s
L
C
Microwave
transmission
line
Signal source
v_{sg}
C_J
JJ
R
Z_0
Z_0
Second stage
amplifier

Fig. 4

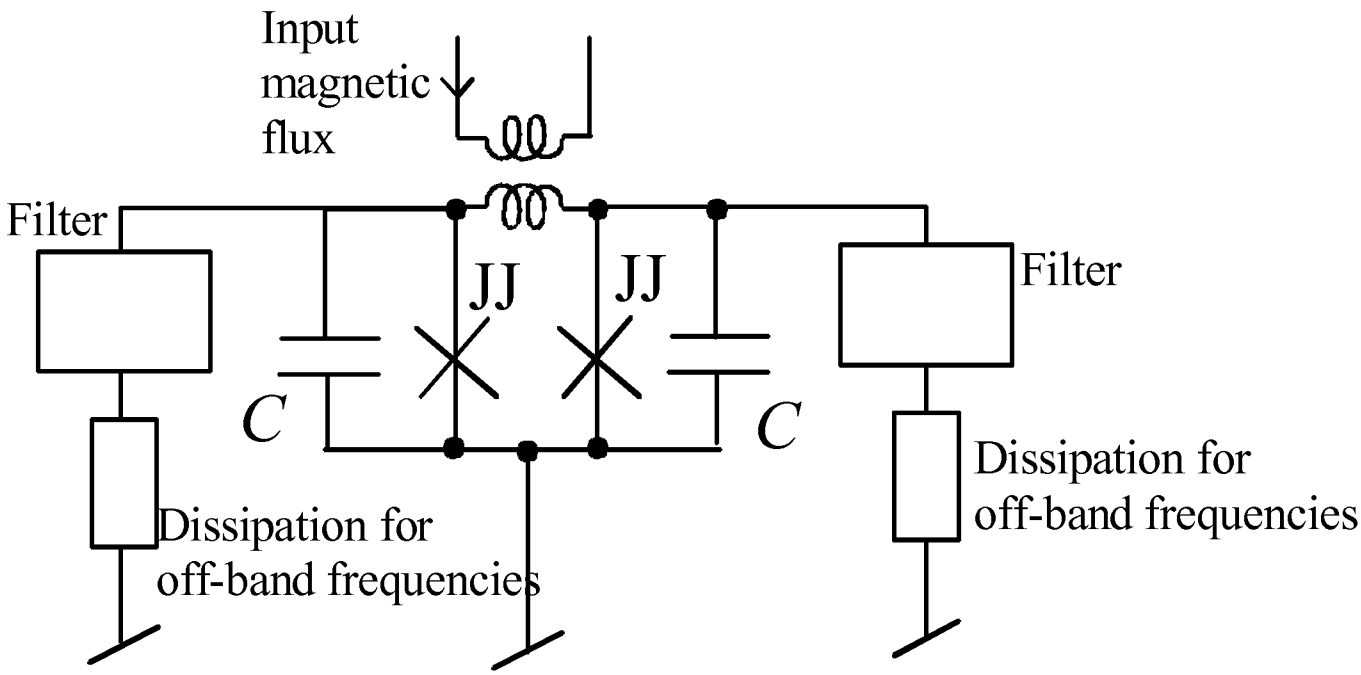

Input
magnetic
flux
Filter
JJ
JJ
Filter
C
C
Dissipation for
off-band frequencies
Dissipation for
off-band frequencies

Fig. 5

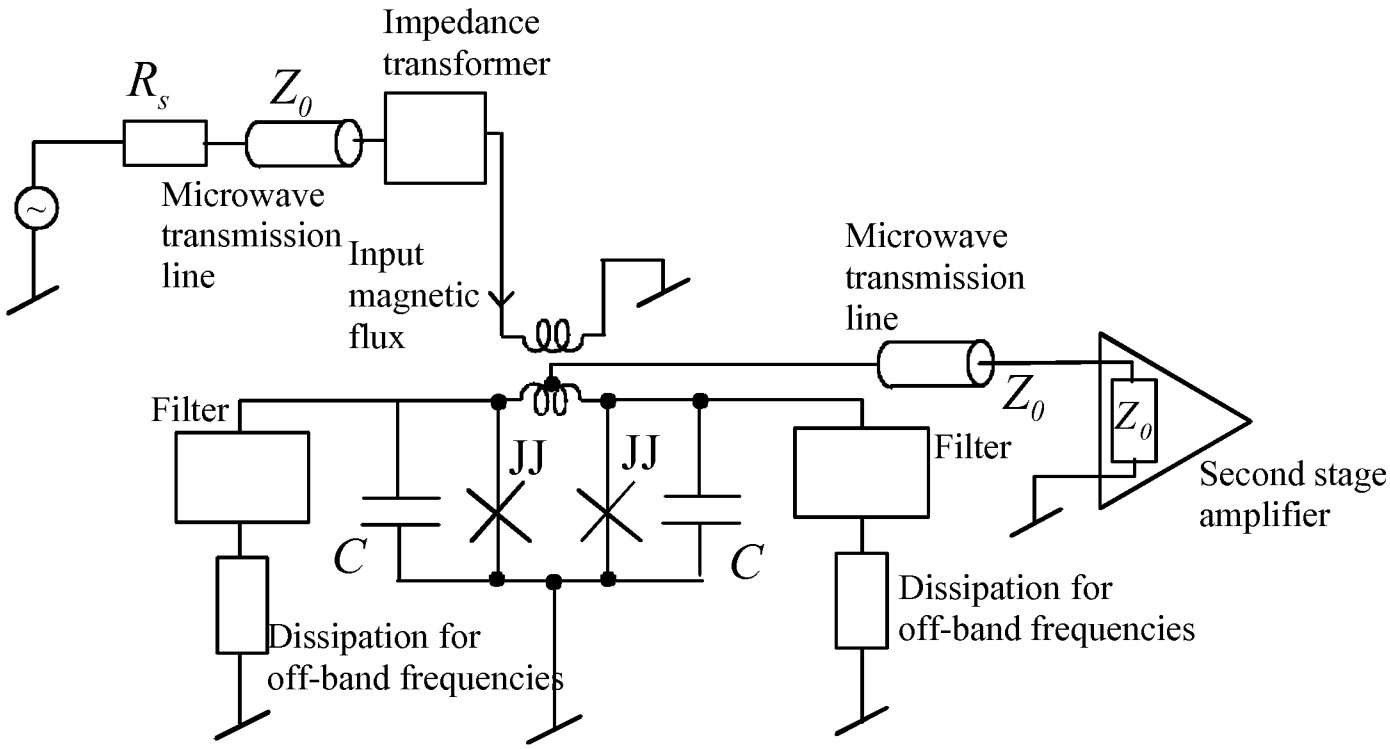

Impedance transformer
R_s
Z_0
Microwave transmission line
Input magnetic flux
Microwave transmission line
Z_0
Z_0
Filter
JJ
JJ
Filter
Second stage amplifier
C
C
Dissipation for off-band frequencies
Dissipation for off-band frequencies

Fig. 6

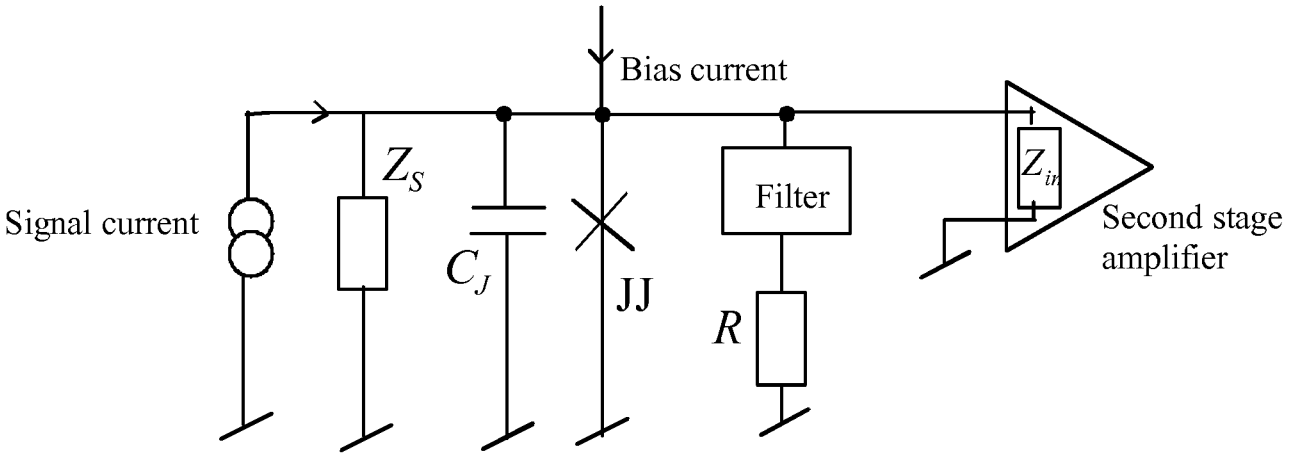

Bias current
Signal current
Z_S
C_J
JJ
Filter
R
Z_{in}
Second stage amplifier

Fig. 7

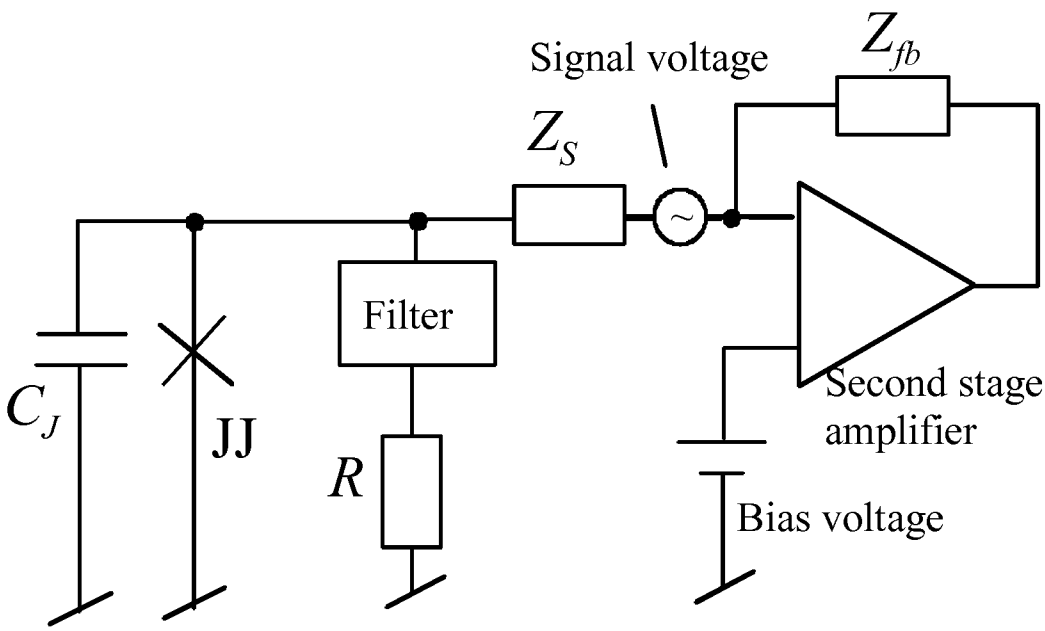

Signal voltage
Z_{fb}
Z_S
Filter
C_J
JJ
R
Second stage amplifier
Bias voltage

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2012/050244

A. CLASSIFICATION OF SUBJECT MATTER

See extra sheet

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: H03F, G01R, H01L

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

FI, SE, NO, DK

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

EPO-Internal, WPI, Internet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 9638737 A1 (VALTION TEKNILLINEN et al.) 05 December 1996 (05.12.1996) page/lines: 3/21-23, 3/31-35, 4/20-22, 4/27-36, 5/3-8, 5/20-23, 5/33-37, 6/1-5, 9/1-2, 9/24-32, 10/3-18, 10/17-18,10/29-38, 11/18-23; Figs. 4-9	1-4, 6, 8, 12-30
X	Seppä, H. et al., Dc SQUID Based on Unshunted Josephson Junctions: Experimental Results, IEEE Transactions on Applied Superconductivity, Vol. 5, No. 2, June 1995, pp. 3248-3251. <DOI: 10.1109/77.403284> pages 3248-3249; Figs. 1-4	1-4, 6, 8, 12-30
X	Yurke, B. et al., Observation of 4.2K Equilibrium Noise Squeezing via a Josephson-Parametric Amplifier, IEEE Transactions on Magnetics, Vol. 25, No. 2, March 1989, pp. 1371-1375. <DOI: 10.1109/20.92550> the whole document	1-2, 12-13, 17-19, 27-30

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 June 2012 (14.06.2012)	20 June 2012 (20.06.2012)

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2012/050244

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 6053762 A (RIKAGAKU KENKYUSHO et al.) 25 February 1994 (25.02.1994) Fig. 1 & abstract [online] EPOQUENET EPODOC & machine translation into English by the JPO [online] [retrieved 4.6.2012] the whole document	
A	US 3636465 A (MACPHERSON ALAN C) 18 January 1972 (18.01.1972) column/lines: 2/19-20; Fig. 1	
P, X	Lähteenmäki, P. et al., Josephson junction microwave amplifier in self-organized noise compression mode, Scientific Reports, Vol. 2, Article 276, 20 February 2012. <DOI: 10.1038/srep00276> whole document & related supplementary information [online], [retrieved on 2012-06-13]. Retrieved from the Internet: <URL: http://www.nature.com/srep/2012/120220/srep00276/full/srep00276.html> the whole document	1-6, 8, 17-30

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/FI2012/050244

Patent document cited in search report	Publication date	Patent family members(s)	Publication date
WO 9638737 A1	05/12/1996	US 6066948 A	23/05/2000
		EP 0829016 A1	18/03/1998
		DE 69531702T T2	08/07/2004
		CA 2223170 A1	05/12/1996
		AU 2569995 A	18/12/1996
		FI 941384 A	11/07/1995
JP 6053762 A	25/02/1994	None	
US 3636465 A	18/01/1972	None	

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2012/050244

CLASSIFICATION OF SUBJECT MATTER

Int.Cl.
H03F 19/00 (2006.01)
G01R 33/035 (2006.01)
H01L 39/02 (2006.01)
H01L 39/22 (2006.01)
H01B 12/00 (2006.01)
H01F 6/00 (2006.01)
G06N 99/00 (2010.01)
B82Y 10/00 (2011.01)