Observation of Zero-Point Noise Squeezing via a Josephson-Parametric Amplifier

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We have demonstrated $(47\pm8)\%$ squeezing of vacuum-fluctuation noise using a Josephson-parametric amplifier operated at 19.16 GHz. The amplifier was operated at 30 mK and has a double-sideband noise temperature of 0.446 K. This is comparable to the vacuum-noise floor $h\nu/2k = 0.460$ K.

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The squeezing of quantum noise has been demonstrated at optical frequencies by a number of groups.[1-6] Here we report the squeezing of quantum noise at microwave frequencies using a Josephson-parametric amplifier. The generation of squeezed microwaves is of interest for a number of reasons. First, squeezed-microwave sources will allow the study of Rydberg atoms interacting with squeezed electromagnetic-field modes. It will thus be possible to explore the new single-atom maser phenomena.[7-9] Second, since squeezed-state generation requires low-noise phase-sensitive amplification, the demonstration of squeezed-microwave generation has been an exercise in low-noise microwave-detector development. In particular,[10] our amplifier has exhibited power gains of 5000 with a single-sideband noise temperature of 1 K at 19.4 GHz. At this frequency, the vacuum-noise floor $\hbar\omega/2k$ is 0.47 K. Such amplifiers, with noise temperatures comparable to the vacuum-fluctuation-noise floor, should make possible the direct observation of nonclassical electromagnetic fields generated in micromasers.[11-14] Finally, Josephson-junction nonlinearities can be strong compared with characteristic quantum voltage or current scales. Using Josephson-junction devices,[15] it should thus be possible to study nonlinear quantum electronics phenomena that would be difficult to study at optical frequencies.

The Josephson-junction-parametric amplifier used in the experiments reported here has the same design as the one used earlier to demonstrate the squeezing of 4.2-K equilibrium noise.[16] Detailed descriptions of the amplifier can be found in Refs. 15–19. The parametric amplifier was operated in the degenerate mode where the pump frequency is twice the signal-carrier frequency. Since the vacuum-fluctuation noise at 19.4 GHz is an order of magnitude smaller than 4.2-K thermal noise, to make feasible the observation of quantum-noise squeezing, a number of improvements in instrumentation had to be made, most important of which was the installation of two cryogenic microwave amplifiers which decreased the detector noise temperature by an order of magnitude to 215 K. The instrumentation used in the present experiment is depicted in Fig. 1.

Vacuum-fluctuation noise or thermal noise is generated by a variable-temperature termination[20] (T) that can

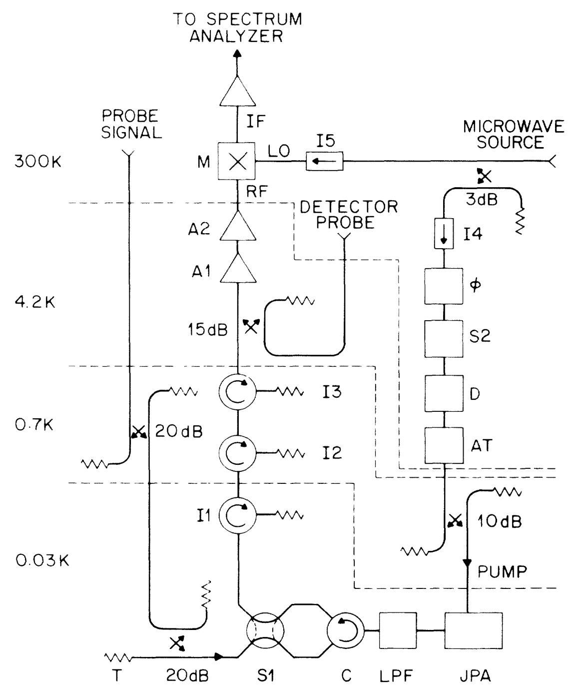

FIG. 1. Instrumentation for the observation of quantum-noise squeezing at microwave frequencies. The symbols denote the following: JPA, Josephson-parametric amplifier; LPF, low-pass filter; C, circulator; S1, waveguide switch; T, variable-temperature termination; M, Schottky-diode mixer; Φ, phase shifter; S2, diode switch; DS, frequency doubler; and AT, attenuator. I1, I2, and I3 are cryogenic isolators, I4 and I5 are room-temperature isolators, and A1 and A2 are HEMT amplifiers. The dashed lines divide the components according to the temperature at which they are operated.

be cycled between 30 mK and 2 K. The noise from this termination is directed by a motorized waveguide switch[21] (S1) toward either the Josephson-parametric amplifier (JPA) or the Schottky-diode mixer (M).[22] When the noise from the termination T is directed toward the JPA, it first passes through the three-port circulator (C) and a low-pass filter (LPF). The low-pass filter blocks pump power from reaching the cold termination T or the mixer. The parametric amplifier is operated in a reflection mode where the amplified or squeezed noise propagates out through the signal input port. The amplified signal is directed through the low-pass filter, circulator, and waveguide switch toward the mixer. Cryogenic isolators[23] I1, I2, and I3 provide 68 dB of isolation from room-temperature radiation propagating from the mixer towards the parametric amplifier. The components T, S1, C, LPF, and JPA are thermally anchored to the mixing chamber of a dilution refrigerator and are cooled to 30 mK. The isolators I2 and I3 are thermally anchored to the still of the mixing chamber and are cooled to 700 mK. Two cryogenic high-mobility transistor (HEMT) amplifiers, A1 and A2, operating at 4.2 K, amplify the signal before it is delivered to the radio-frequency (RF) port of the mixer. The HEMT amplifiers have a 3-dB passband extending from 18 to 20 GHz. The intermediate-frequency (IF) mixer output is amplified and delivered to a spectrum analyzer. The microwave source that provides local-oscillator (LO) power for the mixer also provides the power for the pump. The pump microwaves are obtained by sending the source microwaves through a doubler (D). A computer-controlled phase shifter Φ allows one to adjust the relative phase between the pump and the local oscillator. A diode switch S2 allows one to turn the pump power on and off. The power of the pump is adjusted via the attenuator AT. All of the components M, Φ, S2, D, and AT are operated at room temperature. I4 and I5 are room-temperature isolators. Probe signals injected into the cryostat are attenuated by 20 dB at the still temperature of 700 mK and then attenuated by another 20 dB before being injected into the waveguide between the termination T and the switch S1. Hence, room-temperature thermal noise propagating down the signal-probe waveguide is made negligible by 40 dB of attenuation. A detector probe signal is injected into the input of the first HEMT amplifier A1 via a 15-dB coupler. This probe allows one to monitor the detector-system gain to check for possible saturation effects. The microwaves are piped between room temperature and 4.2 K via 1.5-m-long stainless-steel waveguides. Thermal isolation between components held at 4.2 and 0.7 K and between components held at 0.7 K and 30 mK was provided by 30-cm lengths of stainless-steel waveguide.

The mixer has a dc to 1-GHz, 3-dB passband and performs homodyne detection[24-26] where the signals at frequencies $\nu+\nu_0$ and $\nu-\nu_0$ (ν_0 is the local-oscillator frequency) both generate an output at the intermediate frequency ν. Since the LO and pump are phase locked by virtue of being derived by the same microwave source, the homodyne detector is sensitive to the correlations that the parametric amplifier establishes in the amplitudes at $\nu+\nu_0$ and $\nu-\nu_0$. These correlations give rise to the noise suppression referred to as squeezing.[17,18]

We will regard the detector system as consisting of the spectrum analyzer, IF amplifier, mixer, and all the waveguide components between the mixer and switch S1. This includes amplifiers A1 and A2 and isolators I1, I2, and I3.

In the experiments reported here the LO frequency was set at 19.16 GHz. Noise measurements were made at the frequency of 160 MHz using a Hewlett-Packard model HP8566B spectrum analyzer. A resolution bandwidth of 1 MHz, a video bandwidth of 10 Hz, a frequency span of 1 MHz, and a sensitivity setting of 1 dB/div were employed. In addition, classical gain and loss measurements were made using a probe signal that was offset from the local oscillator by 170 MHz. Detector saturation was monitored with a probe signal that was offset 140 MHz from the local oscillator.

In order to measure the small changes in noise level reported by the spectrum analyzer, two lock-in detector techniques were employed. In the first scheme the cold termination T was cycled between two temperatures; in the second the pump was turned on and off. Let $P_{\rm on}(\nu)$ and $P_{\rm off}(\nu)$ denote the noise power per unit bandwidth that an ideal homodyne detector would measure for the noise entering the input port of the detector when the cold-termination heater is, respectively, on or off. Let $\Delta S(\nu)$ denote the difference in dB of the noise levels reported by the spectrum analyzer when the cold-termination heater is on or off. One then has

$$\Delta S(\nu)=10\log_{10}\left(\frac{1+P_{\rm on}(\nu)/kT_d}{1+P_{\rm off}(\nu)/kT_d}\right), \tag{1}$$

where T_d is the noise temperature of the detector system. Since for our system the intermediate frequency ν is much smaller than the local-oscillator frequency ν_0, the noise power coming from the variable-temperature cold termination is given by

$$P(\nu)=\tfrac{1}{2}h\nu\coth(h\nu_0/2kT), \tag{2}$$

where T is the temperature. The detector-system noise temperature was determined by cycling the cold termination between two known temperatures and measuring $\Delta S(\nu)$. Equations (1) and (2) can be used to determine the detector noise temperature T_d, provided the switch S1 is set so that the detector system looks directly at the cold termination. By cycling the cold termination between 30 mK and 2 K, T_d was measured to be 215 ± 5 K using this method.

The quantum theory of Josephson-parametric amplifiers in connection with microwave squeezing has been discussed by several authors.[17,27,28] The noise power per unit bandwidth $P_{in}(\nu)$ seen by an ideal homodyne detector at the output of a parametric amplifier when the pump is on is

$$P(\nu)=\eta F(\phi)P_{in}(\nu)+(1-\eta^{1/2})[\eta^{1/2}F(\phi)+1]P_{loss}(\nu)\,, \tag{3}$$

where $P_{in}(\nu)$ is the power spectrum at the input port and P_{loss} is the power spectrum of the noise emitted by the losses internal to the parametric amplifier, η is the reflection coefficient of the JPA when the pump is off, and ϕ is the relative phase between the local oscillator and the pump. The function

$$F(\phi)=2G-1+2G^{1/2}(G-1)^{1/2}\cos(2\phi) \tag{4}$$

characterizes the phase-sensitive gain of the JPA. $P_{loss}(\nu)$ has the same form as Eq. (2) where T is now the temperature of the JPA losses. For the measurements reported here the temperature of the JPA was 30 mK. The homodyne-detector power spectrum $P(\nu)$ when the pump is off is obtained from Eq. (3) by setting $F(\phi)=1$.

The efficiency η can be determined by measuring ΔS as one cycles the cold termination between two temperatures, provided the switch S1 is set so that the termination noise propagates through the JPA and the pump is off. Once η has been determined the same method can be used to extract $F(\phi)$ by turning the pump on.

Squeezing was observed by measuring the change ΔS in the spectrum analyzer's noise floor when the pump is turned on and off, and the cold termination is held at a fixed temperature. Figure 2 shows data obtained during a typical squeezing run. The data represented by triangles were obtained when the cold termination was cooled to 30 mK. In this case the noise emitted by the termination equals the vacuum-fluctuation noise to 1 part in 10^{13}. The data represented by circles were taken when the temperature of the termination was at 1.072 K. In this case the noise emitted by the termination is approximately twice as large as the vacuum-fluctuation noise. For this run, the efficiency η was measured to be 0.382, and the maximum value of $F(\phi)$ was measured to be 4.43. The dashed and solid curves of Fig. 2 are the theoretical predictions based on Eqs. (1)-(4). Note that there are no adjustable parameters since η, $F(\phi)$, ϕ, T_d, and the temperatures of the cold termination and the JPA are all independently measured quantities. The noise drop observed during the run at which the cold termination was at 30 mK is $\Delta S=-0.450\times10^{-2}$ dB, a drop $\Delta T=T_d(1-10^{\Delta S/10})$ of 0.223 K relative to the pump-off noise floor. Assuming that the pump-off noise floor consists entirely of vacuum fluctuations $h\nu_0/2k=0.46$ K, this noise drop corresponds to a quantum-noise squeezing of 49%.

The possibility that detector saturation could account

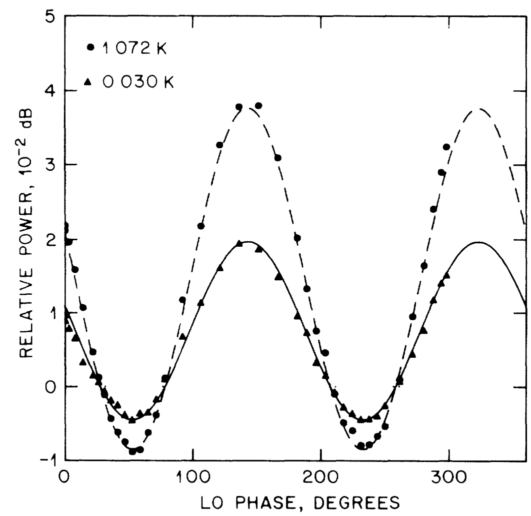

FIG. 2. Spectrum-analyzer noise power referenced to the pump-off noise floor as a function of the local-oscillator phase. The data represented by triangles were taken with the cold termination at 30 mK. These data exhibit a 0.45×10^{-2}-dB (0.223-K) drop in the noise for certain LO phases, corresponding to 47% squeezing below the vacuum-noise floor. The circles represent data taken with the cold termination at 1.072 K.

for the observed squeezing was ruled out in a separate experiment in which a probe signal, offset from the LO by 140 MHz, was injected into the input of the first amplifier A1 in the detector system in order to monitor detector gain while the JPA noise was measured at an intermediate frequency of 160 MHz. The detector-system gain remained constant to within 0.7×10^{-3} dB while the noise level $\Delta S(\nu)$ exhibited 3.2×10^{-3}-dB squeezing. This bound on the detector saturation provides the main uncertainty in the measured degree of squeezing (49 ± 8)% relative to the pump-off noise floor.

In order to demonstrate that the noise at the input port of the parametric amplifier, when the pump is off, consists essentially of vacuum-fluctuation noise, the relative phase ϕ between the pump and the LO was adjusted so that the mixer would detect the maximally amplified quadrature of the JPA output. The difference ΔS between the pump-on and pump-off noise floors was measured as a function of cold-termination temperatures. These data are depicted in Fig. 3. The efficiency η for this run was measured to be 0.346. The data were fitted by Eq. (3) using

$$P_{in}(\nu)=\tfrac{1}{2}h\nu_0[\coth(h\nu_0/2kT)+B]\,, \tag{5}$$

where B accounts for a possible extra noise source at the JPA's signal port. $F(\phi)$ and B were fitting parameters. The solid curve in Fig. 3 represents the fit to the data. From the fit, one obtains $B=(3.4\pm2.0)\times10^{-2}$ and $F(\phi)=4.437\pm0.043$. Hence, the noise entering the input is within 3.4% of the vacuum-noise floor. Taking this noise into account, the observed noise drop of 0.223

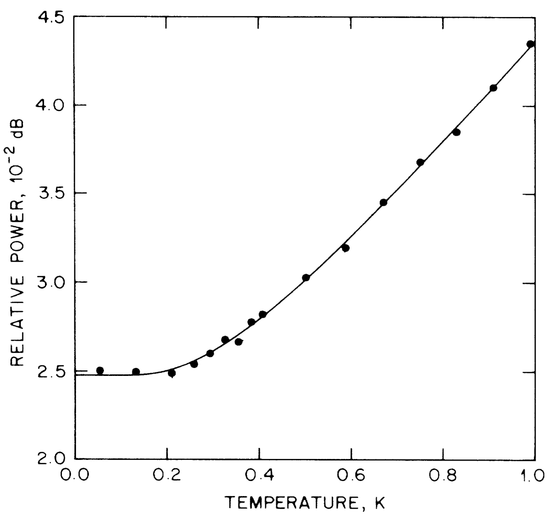

FIG. 3. The noise in the amplified component of the output of the Josephson-parametric amplifier as a function of the input-termination temperature. The data map out the blackbody noise emitted by the termination. The solid curve is a fit to the data in which an extraneous noise source is included as a fitting parameter. The difference between the solid curve and the dotted curve indicates the size of the extraneous noise.

K represents a squeezing of $(47\pm8)\%$ below the vacuum-noise floor. Further, because of the good agreement between the data and the theory, Eqs. (1)-(4), the parametric amplifier's double-sideband noise temperature, 0.446 K, is accounted for by the vacuum noise emitted by the amplifier's losses.

In conclusion, we have observed a 223-mK drop in the noise emitted from a Josephson-parametric amplifier operated at 19.16 GHz and cooled to 30 mK. The drop is relative to the pump-off noise level which we have established to be only 3.4% greater than the vacuum-noise floor. Hence, we have observed $(47\pm8)\%$ squeezing below the vacuum-noise floor, the uncertainty being determined by the measured upper bound on the degree of detector saturation.

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