Observation of 4.2-K Equilibrium-Noise Squeezing via a Josephson-Parametric Amplifier

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We have demonstrated 42% squeezing of 4.2-K thermal noise using a Josephson-parametric amplifier operated at 19.4 GHz. The amplifier has been operated at 0.1 K with an excess noise of 0.28 K referred to the input port. This is less than the vacuum fluctuation noise $h\nu/2k=0.47$ K at 19.4 GHz. The amplifier thus is less noisy than a linear phase-insensitive amplifier such as a maser could in principle be.

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Recently there has been considerable experimental success in the generation of squeezed states at optical frequencies.[1] Because of their promising utility in sensitive measurement,[2] it is desirable to devise squeezed-state sources over a broad range of the electromagnetic spectrum. We are engaged in an effort to generate squeezed microwaves[3] in the *K* band, 18–26.5 GHz. Such a source should allow the study of Rydberg atoms interacting with squeezed microwaves.[4] As a promising step we have demonstrated the squeezing of 4.2-K equilibrium noise using a Josephson-parametric amplifier (JPA). A 1.8-K drop (42% squeezing) was observed in one amplitude component of the noise emitted by the JPA. The squeezing of thermal noise is of interest in its own right since it can be used as a noise-reduction technique even when a system is not performing near the quantum limit. In particular, back-action-evasion detection techniques[5] work on thermal noise[6,7] and are of interest in connection with increasing the sensitivity of Weber-bar gravitational-radiation detectors.

JPA's are notorious for their poor noise performance.[8,9] Recently, however, good noise performance has been achieved with rf superconducting-quantum-interference-device (SQUID) parametric amplifiers.[10,11] Our JPA has been operated at 0.1 K with an excess noise of 0.28 K when referred to the amplifier's input. Since at our operating frequency, 19.4 GHz, the quantum noise floor $\hbar\omega/2k$ is 0.47 K, the device has been operated in a domain dominated by quantum noise. The JPA, in fact, exhibits less internal noise than a linear phase-insensitive amplifier such as a maser must exhibit because of spontaneous emission.[5]

The circuit diagram for our JPA is shown in Fig. 1. Two Josephson junctions (J) form a dc SQUID. Magnetic flux is coupled into this SQUID via the inductors L_s through the $+I_c$ and $-I_c$ current-bias lines. In this manner the critical current of the effective junction formed by the parallel combination of the two junctions can be adjusted for optimum performance. The phase of the effective junction is controlled by the current-bias line I_ϕ. The junctions are in parallel with an *LC* resonator consisting of the parallel combinations of capacitors *C* and inductors *L*. Since the Josephson junction and inductors are in parallel and form an rf SQUID loop, the overall circuit can be viewed as an rf-SQUID–parametric amplifier. The JPA is operated in the degenerate mode where the pump current propagating along the 50-Ω transmission line oscillates at 38.8 GHz (twice the carrier frequency of the signal). This current modulates

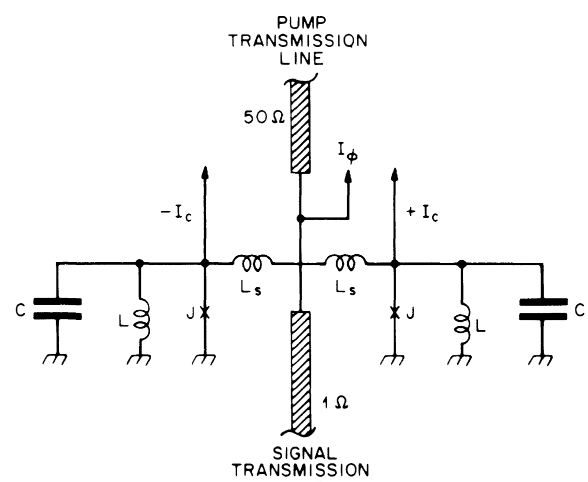

FIG. 1. A Josephson-parametric amplifier. See text for details.

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the nonlinear inductance of the Josephson junction, creating an effective time-dependent inductance as seen by the LC resonator. This time-dependent inductance does parametric work to amplify the signal propagating in along the 1-Ω transmission line. The device is operated in the reflection mode in which the amplified signal propagates back out along the 1-Ω transmission line. The 1-Ω impedance is transformed to 50 Ω via a four-stage impedance transformer consisting of various lengths of strip line and coplanar waveguide as described in Table I. The 3-dB passband of the JPA was measured to be 1 GHz.

The circuit and impedance transformer were fabricated on a 1×1 cm^2 silicon substrate. The junctions, having a 50-μm^2 area, were fabricated for a critical current of a 200 A/cm^2 with use of a niobium/aluminum-oxide technology.[12] The inductors L_s consisted of a 0.5-pH length of transmission line between the junctions. The rf-SQUID inductance $L/2$ was 2.9 pH. The capacitors C were designed so that the total parallel capacitance of the capacitors and Josephson-junction capacitances would be 18.1 pF. The bias lines consisted of coplanar waveguides with impedances of 50 Ω in order not to load the device whose characteristic impedance is 1 Ω. Microwave power was coupled onto and off of the chip through SMA connectors followed by coaxial-to-waveguide transitions.

The instrumentation for data taking is depicted in Fig. 2. The microwave signals were piped into and out of the cryostat through stainless-steel waveguides (WR-42 for the signal waveguides; WR-22 for the pump) 1.5 m long. A diode mixer[13] having a dc to 1 GHz i.f. band was employed as the detector. The local oscillator, 19.4 GHz, was derived from the same microwave source as the pump via a 3-dB directional coupler. The power delivered to the pump was doubled to 38.8 GHz via doubler D. An electronic phase shifter ϕ in the pump line (before the doubler) allows one to adjust the relative phase between the pump and local oscillator (LO). The mixer M together with its following amplifier A and spectrum analyzer has an overall system noise temperature T_d of 660 ± 20 K as measured with a variable-temperature termination. The total attenuation measured from the output port of the JPA to the rf port of the mixer was $\eta_d = 0.28\pm 0.02$ or 5.5 dB.

The amount of room-temperature microwave noise delivered to the JPA along the probe-signal waveguide is made negligible via a 40-dB hybrid coupler. Essentially all the equilibrium noise delivered to the input port of the JPA thus comes from the cold termination T. Thermal noise propagating from the mixer to the output port of the JPA is blocked via the three cryogenic isolators I1, I2, and I3 whose overall isolation was measured to be 68 dB. A waveguide switch S1 can be switched between the JPA and a short in order to make accurate reflection measurements.

The JPA and cold termination T were bolted to the mixing chamber of a dilution refrigerator and could be cooled to 0.1 K. The switch S1, circulator C, and isolators I1, I2, and I3 were heat sunk to the dilution refrigerator's still. 20-cm lengths of stainless-steel waveguide provided thermal isolation between these two sets of components.

With the local oscillator phase locked to the pump, the

TABLE I. The successive lengths of coplanar waveguide and microstrip line used to construct the 50- to 1-Ω impedance transformer.

Impedance (Ω)	Section	Angle (deg)
50	End	
35	Coplanar waveguide	90
1	Microstrip	3.5
50	Coplanar waveguide	13
3.7	Microstrip	90
1.4	Microstrip	90
1	End	

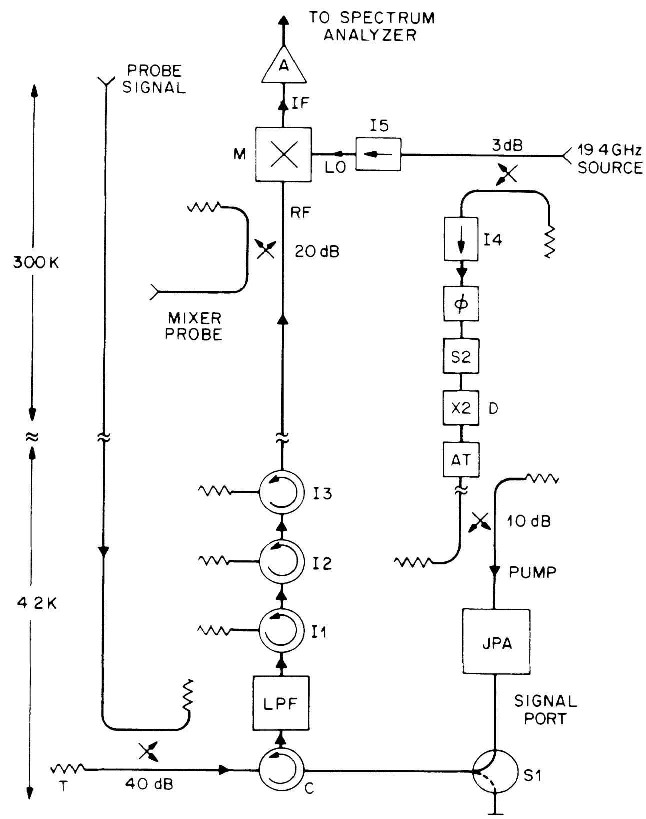

FIG. 2. Microwave instrumentation. The breaks indicate which components are at room temperature and which are at 4.2 K. A low-pass filter (LPF) blocks pump power from reaching the mixer M. I4 and I5 are isolators. AT is a variable attenuator. See text for explanation of the other components.

mixer performs homodyne[14] detection in which the signal at frequency $\nu_0+\nu$ (ν_0 is the LO frequency) and the idler at frequency $\nu_0-\nu$ are both mapped to the same i.f. frequency ν by the mixer.

In order to measure the small changes in the noise level reported by the spectrum analyzer, a lock-in detection technique was employed in which the pump was switched on and off via switch S2 of Fig. 2. The resulting differenced power spectrum $\Delta S(\nu)$ at i.f. frequency ν is

$$\Delta S(\nu)=10\log_{10}\left[\frac{1+\eta_d S_{\rm on}(\nu)/kT_d}{1+\eta_d S_{\rm off}(\nu)/kT_d}\right], \quad (1)$$

where $S_{\rm on}(\nu)$ and $S_{\rm off}(\nu)$ are the power spectra of the signal, as seen by an ideal homodyne detector, at the output of the JPA when the pump is on and off, respectively, and k is Boltzmann's constant. All the noise measurements reported here were taken with 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 setting of 1 dB/div were employed. The average noise level of a given spectrum-analyzer trace was recorded with a computer. Typically 150 such readings were averaged per setting of the local oscillator phase ϕ.

If we assume that the JPA losses (such as Josephson-junction shunt resistances) all appear in parallel,[3,15] then

$$S_{\rm on}(\nu)=\eta F(\phi)S_{\rm in}(\nu) + (1-\eta^{1/2})[\eta^{1/2}F(\phi)+1]S_{\rm loss}(\nu), \quad (2)$$

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

$$F(\phi)=2G-1+2G^{1/2}(G-1)^{1/2}\cos 2\phi \quad (3)$$

describes the phase-sensitive gain of the JPA as seen by a homodyne detector, where G is the power gain for the signal at $\nu_0+\nu$. The pump-off spectrum $S_{\rm off}$ is obtained by our setting $F(\phi)=1$ in Eq. (2).

When an intense probe signal at frequency $\nu_0+\nu$ is injected into the input of the JPA, Eq. (1) reduces to

$$\Delta S(\nu)=10\log_{10}[F(\phi)]. \quad (4)$$

Thus, $F(\phi)$, G, and ϕ can be measured with a classical probe. When only thermal equilibrium noise is present and the cold termination and the JPA are at the same temperature T, then (since $\nu \ll \nu_0$)

$$S_{\rm in}(\nu)=S_{\rm loss}(\nu)=\tfrac{1}{2}h\nu_0\coth(h\nu_0/2kT). \quad (5)$$

Figure 3 shows the experimentally measured noise power level $\Delta S(\nu)$ as a function of ϕ for the case when all the low-temperature microwave plumbing is held at 4.2 K with the aid of 1 Torr of helium exchange gas. These data were taken at $\nu=70$ MHz. With use of a classical probe, the classical gain G was measured to be 1.48. Also, the reflection loss η was measured to be 0.38 (4.2-dB loss) by comparison of the reflection from the JPA, with the pump off, to that of a short (with use of waveguide switch S1). The solid curve in Fig. 3 is a comparison of theory [Eqs. (1)-(3) and (5)] with the data. There are no adjustable parameters since G, η, ϕ, T, η_d, and T_d are all independently measured. From the observed maximum noise reduction $\Delta S=-3.7\times10^{-3}$ dB, a drop $\Delta T=(T_d/\eta_d)(1-10^{\Delta S/10})$ of 1.8 K below the 4.2-K equilibrium noise floor can be inferred. This corresponds to a 42% squeezing of the equilibrium noise.

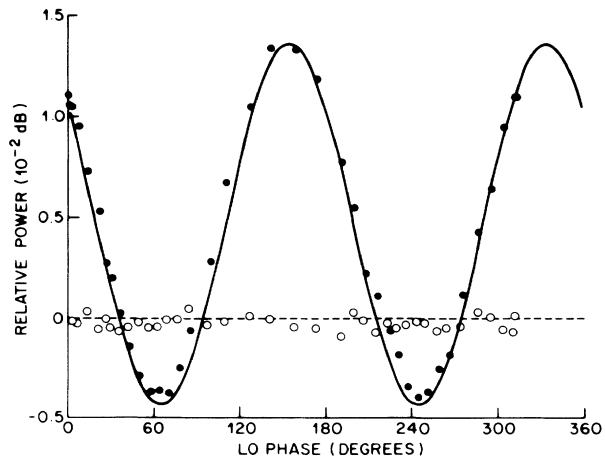

FIG. 3. Thermal-equilibrium-noise squeezing at 4.2 K. The open-circle data, taken with AT of Fig. 2 set for a maximum attenuation, establish the baseline. When pump power is delivered to the Josephson-parametric amplifier the noise (filled circles) drops below the baseline for certain settings of the relative phase between the LO and the pump. The smooth curve is a comparison of theory with experiment with no adjustable parameters.

The possibility that detector saturation could be affecting the measurements was ruled out in a separate experiment in which a probe signal was injected into the mixer at a frequency offset from the LO by 55.6 MHz to monitor the mixer gain while the JPA's noise was measured at an i.f. frequency of 70 MHz. The mixer gain remained constant to within $\pm5\times10^{-4}$ dB while the noise level $\Delta S(\nu)$ exhibited 3×10^{-3}-dB squeezing.

In order to demonstrate that the pump-off noise floor (the zero of Fig. 3) is 4.2-K equilibrium noise, the JPA and the cold termination T were cooled to 0.1 K. The JPA was adjusted for a gain G of 1.60 and the reflection loss η was measured to be 0.50 (3 dB). The phase ϕ was adjusted for a maximum gain. The expected ΔS from Eqs. (1)-(3) and (5) is 1.92×10^{-3} dB. The measured ΔS was $(2.82\pm0.04)\times10^{-3}$ indicating an excess noise of $(9.0\pm0.4)\times10^{-4}$ dB (0.44 ± 0.02 K).

Viewed as being generated internally, the noise can be referred to the JPA's input by division by $\eta[F(0)-1]$. One then obtains 0.28 K for the JPA's noise temperature. When viewed as noise coupled into the cryostat from the outside, this noise contributes 6% to the 4.2-K equilibrium noise. Since the signal measured is the difference between the pump-on and the pump-off noise levels, it has thus been established that the y-axis zero of Fig. 3 is the 4.2-K equilibrium noise floor to within 6%.

In conclusion, we have measured a 1.8-K drop (42% squeezing) in the noise emitted from a Josephson-parametric amplifier. This drop is relative to the pump-off noise level which we have established to be 4.2-K equilibrium noise to within 6%. Further, we have demonstrated that there is no significant detector saturation effect.

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[1]R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, Phys. Rev. Lett. **55**, 2409 (1985); R. M. Shelby, M. D. Levenson, S. H. Perlmutter, R. G. DeVoe, and D. F. Walls, Phys. Rev. Lett. **57**, 691 (1986); L. Wu, H. J. Kimble, J. L. Hall, and H. Wu, Phys. Rev. Lett. **57**, 2520 (1986); M. W. Maeda, P. Kumar, and H. J. Shapiro, Opt. Lett. **3**, 161 (1986); S. Machida, Y. Yamamoto, and Y. Itaya, Phys. Rev. Lett. **58**, 1000 (1987).

[2]M. Xiao, L. Wu, and H. J. Kimble, Phys. Rev. Lett. **59**, 278 (1987); P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, Phys. Rev. Lett. **59**, 2153 (1987); C. W. Gardiner, Phys. Rev. Lett. **56**, 1917 (1986).

[3]B. Yurke, L. W. Rupp, and P. G. Kaminsky, IEEE Trans. Mag. **23**, 458 (1987); B. Yurke, E. A. Whittaker, L. R. Corruccini, P. G. Kaminsky, L. W. Rupp, A. D. Smith, A. H. Silver, and R. W. Simon, to be published.

[4]D. Meschede, H. Walther, and G. Müller, Phys. Rev. Lett. **54**, 551 (1985).

[5]C. M. Caves, K. S. Thorne, R. W. P. Drever, V. D. Sandberg, and M. Zimmermann, Rev. Mod. Phys. **52**, 341 (1980).

[6]M. F. Bocko and W. W. Johnson, Phys. Rev. Lett. **48**, 1371 (1982), and Phys. Rev. A **30**, 2135 (1984).

[7]G. W. Spetz, A. G. Mann, W. O. Hamilton, and W. C. Oelfke, Phys. Lett. **104A**, 335 (1984).

[8]P. L. Richards, *SQUID '76: Superconducting Quantum Interference Devices and Their Applications,* edited by H. D. Hallbohm and H. Lubbig (Walter de Gruyter, Berlin, 1977), pp. 323–338.

[9]N. F. Pedersen, *SQUID '80: Superconducting Quantum Interference Devices and Their Applications,* edited by H. D. Hallbohm and H. Lubbig (Walter de Gruyter, Berlin, 1980), pp. 739–762.

[10]N. Calander, T. Claeson, and S. Rudner, J. Appl. Phys. **53**, 5093 (1982).

[11]A. D. Smith, R. D. Sandell, J. F. Burch, and A. H. Silver, IEEE Trans. Mag. **21**, 1022 (1985).

[12]M. Gurvitch, M. A. Washington, and H. A. Huggins, Appl. Phys. Lett. **42**, 472 (1983).

[13]The mixer, model CK-1, was manufactured by Honeywell Spacekom, 214 East Gutierrez Street, Santa Barbara, CA 93101.

[14]H. P. Yuen and J. H. Shapiro, IEEE Trans. Inf. Theory **26**, 78 (1980); H. P. Yuen and V. W. S. Chan, Opt. Lett. **8**, 177 (1983); B. L. Schumaker, Opt. Lett. **9**, 189 (1984); B. Yurke, Phys. Rev. A **32**, 311 (1985).

[15]C. M. Caves, Phys. Rev. D **26**, 1817 (1982); B. Yurke and J. S. Denker, Phys. Rev. A **29**, 1419 (1984); B. Yurke, J. Opt. Soc. B **4**, 1551 (1987).