A low-noise series-array Josephson junction parametric amplifier

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We have obtained parametric gain at 19 GHz from a distributed Josephson junction parametric amplifier whose active gain medium consists of a series array of 1000 Josephson junctions embedded in a coplanar waveguide. When cooled to 1.7 K the amplifier provides 16 dB gain in a mode where the internally generated double sideband noise referred to input is 0.5 ± 0.1 K. This noise is consistent with Nyquist noise generated from the losses. An instantaneous bandwidth of 125 MHz has been observed with a peak gain of 12 dB. The 3 dB compression point with a peak gain of 14.6 dB is -90.5 dB and the dynamic range is 38 dB. © *1996 American Institute of Physics.* [S0003-6951(96)03546-2]

There has been considerable interest in Josephson junction parametric amplifiers given their potential for use as very low noise instrumentation amplifiers[1] in the microwave frequency range. Early Josephson parametric amplifiers have tended to be very noisy, as discussed in the review by Feldman *et al.*[2] More recently, considerable success in obtaining low noise performance from Josephson parametric amplifiers[3–7] has been achieved. In fact, Josephson parametric amplifers with double sideband noise performance exceeding the quantum limit for linear phase-insensitive amplifiers[8] have been used to generate squeezed states of the electromagnetic field at 20 GHz. However, a drawback of these amplifiers is their narrow bandwidth. In order to obtain large bandwidths it is desirable to avoid the use of resonant structures to impedance match 50 Ω signals to the low impedance exhibited by a Josephson junction. It has been realized that impedance matching problems could be circumvented through the use of a series array of Josphson junctions[9,10]. Here we report very low noise operation in a parametric amplifier consisting of a series array of 1000 Josephson junctions forming the center conductor of a coplanar waveguide. This configuration constitutes a distributed parametric amplifier since the length of the array of junctions, 9 mm, greatly exceeds the calculated wavelength of 0.65 mm for the 19 GHz signals propagating along the coplanar waveguide. Distributed parametric amplifiers of this type have been discussed in the literature[11]. The amplifier was pumped at the signal carrier frequency, the so-called doubly degenerate mode of operation.

Our devices were fabricated in their entirety by the PARTS process developed at IBM[12]. The parametric amplifier used for the results reported here was fabricated on a 0.5 in. $\times$ 0.25 in. silicon substrate. The width of the center conductor in the coplanar waveguide was nominally 8 μm and the gap between the center conductor and each of the ground planes to either side was 5 μm. The 2 μm$\times$2 μm Josephson junctions were along the center conductor and spaced 8μm apart. The trilayer used to form the junctions consisted of 200 and 150 nm niobium base and counterelectrodes, respectively, separated by an oxidized 5 nm aluminum layer to form the barrier. The *I-V* curves for the series array of junctions indicated that the average junction critical current was 12 μA with a $\pm$20% spread. The coplanar waveguide was calculated to have a capacitance per unit length of[13] 187 pF m^{-1}. Due to the inductance of the Josephson junctions, the inductance per unit length depends on the current flowing through the waveguide. Parametric gain results from the work performed on weak signals when this nonlinear inductance is supplied with a pump current. At zero-current bias the coplanar waveguide was calculated to have an inductance of 34.5 μH m^{-1}. Consequently the calculated transmission line impedance and velocity of propagation were, respectively, 430Ω and 1.25×10^7 m s^{-1}. We had hoped for a much higher critical current density that would have brought the transmission line impedance closer to 50 Ω. Nevertheless, the present device worked well; we report on its performance below. A microwave coaxial connector (SMA type marketed by Omni Spectra) at each end of the coplanar waveguide coupled the transmission line to 50 Ω. By terminating one end with a short, the Josephson transmission line was operated at zero bias as a reflection-mode parametric amplifier. The incoming signals entered the same port through which the amplified signal left. This single port also served as the pump port. The amplifier was operated in the doubly degenerate mode in which the pump frequency lies in the signal passband. The input and output signals were separated from each other by a cryogenic circulator. Between the amplifier and the circulator was a waveguide switch that allowed replacement of the amplifier by a short, enabling accurate gain and loss measurements.

The parametric amplifier was connected to cryogenic test instrumentation through a coax-to-waveguide transition. This test instrumentation is the same as described elsewhere[3,8,14] with the minor modification that signals brought in from outside of the cryostat were coupled to the input of the parametric amplifier through a 20 dB directional coupler rather than the two 20 dB couplers (provding 40 dB of coupling) we used in the past. In addition, cooling was provided by thermal conduction to a helium bath rather than by operating a dilution refrigerator. By pumping on the bath, the device temperature could be varied from 4.2 K to 1.7 K. Signals coming from outside the cryostat propagated through 1.5 m of stainless steel waveguide before reaching the 20 dB coupler. This section of waveguide had a loss of 3.2 ± 0.3

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dB. It was estimated that 300 K thermal noise propagating down the waveguide and through the directional coupler was attenuated to a level of 1.9±0.2 K upon arriving at the input of the parametric amplifier. The uncertainty reflected the uncertainty in the temperature profile along the length of the waveguide. With the experiments run at 1.7 K the parametric amplifier saw this noise in addition to that emanating from a cryogenic variable temperature termination (see below) at the other port of the directional coupler. The parametric amplifier thus saw a total of 3.6 K of noise at its input port.

Measurements were performed in the *K*-band (18–26.5 GHz) near 19 GHz. The detector chain consisted of a series chain of three isolators followed by two cryogenic microwave amplifiers followed by a room temperature mixer. Signal and noise measurements were made from spectrum analyzer traces of the mixer's intermediate frequency (IF) output. The thermometer at the variable temperature termination was calibrated from 1.7 K to 4.2 K against the ^{4}He vapor pressure curve. It was possible to extend the thermometer calibration to 6 K by observing changes in the noise of the detector chain. This was done by replacing the parametric amplifier with a short and using a resistive heater to vary the temperature of the cold termination. The detector chain noise temperature was similarly, and independently, calibrated. Since both the mixer's signal and image band lay within the *K* band, the difference in the detector system gain at the signal and the image frequency were taken into account in the noise calibration.

For measurements reported here the pump frequency and power were chosen to be 19.1374 GHz and, typically, -64 dB, respectively. Using probe signals injected from outside the cryostat, the parametric amplifier's loss η with the pump absent was measured by switching between the amplifier and the short. In this manner it was determined that η is constant to within 10% over the passband of the amplifier and was measured to be $\eta=0.64=-1.9$ dB. The probe signals were also used to measure the ratio of the pump-on to pump-off power gain. We denote this ratio by G and refer to it as the parametric gain. The single sideband power gain is given by ηG. For these measurements probe signals 40 dB smaller than the pump were used. It was observed that as the pump power is increased from low values the gain of the amplifier first increases then, after passing through a maximum, decreases again. We will call the point at which the maximum gain is achieved the threshold value. The region where the gain increases with increasing pump power is called the below-threshold region. The region where the gain decreases is called the above-threshold region.

The noise measurements were made with the mixer's local oscillator at 18.5000 GHz and the probe frequency set at 19.145 GHz. The detector system noise temperature at this probe frequency was measured to be 287 K and the parametric amplifier was cooled to 1.72±0.01 K.

Letting T_R denote the temperature of the noise propagating from the amplifier when the pump is off, T_{in} the temperature of the noise propagating into the input port of the amplifier, and T_{loss} the physical temperature of the amplifier, gives

$$T_R=\eta T_{in}+(1-\eta)T_{loss}. \tag{1}$$

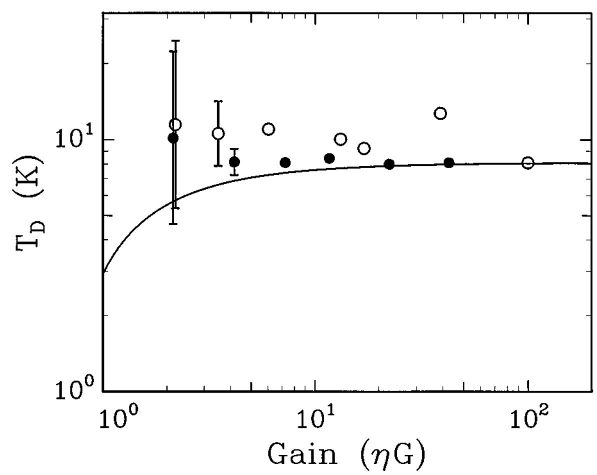

FIG. 1. The difference between the pump-on noise and the reference noise referred to input using the single sideband power gain ηG. The error bars indicate uncertainty in the data due to detector saturation effects. Open circles represent data taken below threshold; filled circles represent data taken above threshold. The solid curve represents the theoretical prediction.

For $\eta=0.64$, $T_{in}=3.6$ K, and $T_{loss}=1.7$ K one obtains $T_R=2.9$ K. Let T_P denote the temperature of the noise propagating from the amplifier when the pump is on. T_P-T_R is measured by noting the change in the IF noise when the pump is turned on and off. Let T_D denote this difference in noise temperatures referred to the amplifier's input,

$$T_D=\frac{T_P-T_R}{\eta G}. \tag{2}$$

The measured T_D for our data runs are depicted in Fig. 1. In measuring T_D we had to account for a 0.27±0.07 dB drop in the pump-on noise floor due to saturation of the detector by the pump.

Also shown in the figure is the theoretical curve obtained from a simple model of a lossy parametric amplifier in which the lossy parametric amplifer was modeled by an ideal parametric ampifier with an attenuator at its input port[14,15]. Although the amount of noise generated internally due to Nyquist noise from the losses depends on how the lossy elements are distributed in and around the active gain medium this model should make reasonable predictions for our device and the model should work particularly well for large gains. According to this model,

$$T_P=\eta(2G-1)T_{in}+\eta^{1/2}(1-\eta^{1/2})(2G-1+\eta^{-1/2})T_{loss}. \tag{3}$$

Let $T_F=T_P/\eta G$ denote the temperature, referred to input, of the noise coming from the output of the parametric amplifer. From Eq. (2) one thus has

$$T_F=T_D+\frac{T_R}{\eta G}. \tag{4}$$

It can be seen from Eq. (3) that the noise T_{in} entering the input port of the amplifier contributes $\eta(2G-1)T_{in}$ to the ouput noise. Hence, we take

$$T_F^{int}=T_F-\frac{2G-1}{G}T_{in} \tag{5}$$

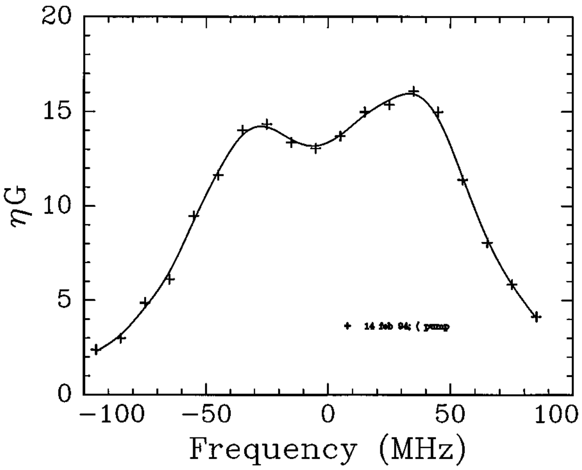

FIG. 2. Gain as a function of frequency for parametric amplifier operation above threshold. The curve is a spline fit to the data. Frequencies are measured relative to the pump frequency of 19.1374 GHz.

to be the internally generated noise, referred to input, of the parametric amplifier. According to the model, T_F^{int} is given by

$$T_F^{int} = \frac{(1-\eta^{1/2})[\eta^{1/2}(2G-1)+1]T_{loss}}{\eta G}. \qquad (6)$$

For $\eta = 0.64$ and $T_{loss} = 1.7$ K, one obtains $T_F^{int} = 0.85$ K in the large gain limit. The experimental values for T_F^{int} can be obtained by using the measured values of T_D in Eq. (4) and Eq. (5), the calculated values of T_R, and the measured values of η and G. Above threshold, at high gains, the amplifier achieves a very good noise performance, $T_F^{int} = 1.0 \pm 0.2$ K, consistent with the 0.85 K of expected internally generated noise. That is, above threshold the internally generated noise is consistent with thermal noise generated in the losses. However, below threshold the experimental values for T_F^{int} are 1 to 6 K above the theoretical prediction, indicating that below threshold there is some noise mechanism other than Nyquist noise generation at work. That the noise should decrease when going from small pump power (drive) to large pump power is unusual for a dynamical system[16] and we do not have a model to account for this observed behavior. The above quoted noise values are those appropriate when the amplifier is used in a single sideband mode of operation. We point out that, if the amplifier was used as a detector to measure broad-band noise entering both the signal and idler port, then the relevant noise values are half those quoted above. In other words, the internally generated double sideband noise is 0.5 ± 0.1 K.

Figure 2 shows the single sideband power gain as a function of frequency, measured for the parametric amplifier when the above threshold pump power was adjusted to give a peak single sideband gain of 12 dB. At this gain the amplifier exhibited a 3 dB passband of 125 MHz. Based on the transmission line calculations one would have expected a gain bandwidth product of $vZ_{in}/(\pi l Z_T)$ where v is the propagation velocity, l is the length of the transmission line, Z_T is the transmission line impedance, and $Z_{in} = 50\ \Omega$ is the impedance into which the transmission line is coupled. The expected gain-bandwidth product of 77 MHz is more than an order of magnitude smaller than that observed. Presumably, stray reactances at the coax to coplanar waveguide transition account for the better than expected coupling.

We have also measured the gain suppression as a function of signal power. Starting with an initial below threshold gain of 16.6, the 3 dB compression point occurs when the signal power reaches -90.5 dB. Using this result, and the fact that the amplifier had an instantaneous bandwidth of 20 MHz, one calculates the noise power to be

$$P = k_B T \Delta f = -128.6 \text{ dB} \qquad (7)$$

and thus, a maximum dynamic range of $-90.5 \text{ dB} - (-128.6 \text{ dB}) \approx 38$ dB.

In conclusion, we have demonstrated very low noise performance (0.5 ± 0.1 K internally generated double sideband noise) from a Josephson parametric amplifier which exhibits a bandwidth of 125 MHz at a peak gain of 12 dB. With a peak gain of 14.6 dB, the amplifier exhibits a 3 dB compression point for signal powers of -90.5 dB. The structure of the amplifier is very simple, consisting of a coplanar waveguide shorted at one end. With a better choice of transmission line impedance and the use of filter structures to tailor the passband the amplifer's performance values could be substantially improved. Such amplifiers may become competitive with *K*-band masers employed in radio astronomy[17].

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