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Low-noise parametric amplification at 35 GHz in a single Josephson tunnel junction

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Parametric amplification at 35 GHz has been obtained using a single Josephson tunnel junction as the active element. The amplifier was operated in the singly quasidegenerate mode with a pump frequency at 70 GHz. The noise temperature was measured and found correlated with the gain. At the highest gain achieved, 11.6 dB, the noise temperature was 400 K. The noise temperature was reduced considerably by decreasing the gain. At 8 and 4 dB we found 165±25 K and 50±30 K, respectively.

PACS numbers: 74.50. + r, 74.30.Gn, 84.30.Dx, 85.25. + k

Parametric amplification in Josephson junctions in the doubly degenerate mode has previously been reported at a frequency as high as 35 GHz using arrays of either microbridges[1] or tunnel junctions,[2] or a single point contact.[3] In this letter we report on a parametric amplifier operated in the singly quasidegenerate mode with the signal, idler, and pump frequencies satisfying $f_s + f_i = f_p$ and $f_s \simeq f_i$. A single Josephson tunnel junction was used as the active element. The properties of the amplifier can easily be tuned by varying the junction dc bias current. This mode of operation was earlier attempted at 35 GHz[3] but no gain was achieved. The present amplifier relies on parametric excitation of the Josephson plasma resonance by an external pump at twice the plasma frequency.[4,5] Just below the threshold for the half-harmonic oscillations the junction may work as an amplifier at frequencies near the plasma frequency.[6] This has already been demonstrated at *X*-band frequencies.[7]

With the 35-GHz setup shown in Fig. 1, including a helium-cooled attenuator ($L_A = 18$ dB) and circulator (isolation 17 dB, insertion loss $L_{23} = 0.25$ dB), in order to reduce incoming room-temperature noise we have obtained a maximum gain of 11.6 dB which was referred to the amplifier port of the circulator (port 2). This was associated with a 3-dB bandwidth of 10 MHz and a noise temperature T_{PA} of 400 K. For gains of the order of 8–9 dB, noise temperatures of 100–150 K were obtained. These results are discussed below. Without the cooled attenuator gains up to 9 dB have been measured at the cryostat top flange.

The elements used were single small-area ($10 \times 10\,\mu$m) Sn-oxide-Pb junctions mounted across a two-section binominal microwave transformer[7] in order to match the low resistance of the junction to the waveguide impedance. The transformer impedance ratio was 58 with a matched 3-dB bandwidth of 3 GHz. As a preliminary attempt to outbalance the inherent film inductance, a two-pin tuning waveguide section was inserted between the transformer and the circulator.

The 70-GHz pump power was coupled into the junction via a waveguide ending at the rear side of the junction substrate. Since the pump power required is in the nanowatt range no attempt was made to match the pump circuit to the junction. The pump was frequency-locked to the local oscillator and both pump and signal powers were leveled.

The transmission line from the circulator to the balanced mixer consisted of a 0.6-m stainless-steel waveguide with an attenuation L_0, a two-way microwave switch, three isolators giving 90 dB of isolation, and a harmonic rejection filter with 80-dB attenuation at 70 GHz. The i.f. frequency was 100 MHz (i.f.-band 5–250 MHz) and the i.f. amplifier output was displayed on a spectrum analyzer with a resolution bandwidth $B_{SA} = 300$ kHz. Using the switch the input signal could be applied either to the junction or directly to the receiver. Hence, the amplifier gain could be measured by a simple substitution. The insertion loss of the input waveguide, the cooled attenuator and circulator, and the output waveguide was measured to 23.6 dB with a short mounted on port 2. The properties of the amplifier are referred to this port.

With a given spectrum analyzer center frequency within the i.f. bandwidth, the *Y* deflection is proportional to the

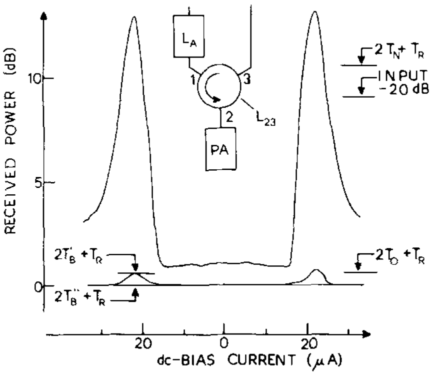

FIG. 1. Recieved power versus dc bias currents at the signal frequency (upper curve) and ~ 1 MHz away from the signal frequency (lower curve) with $f_s = 36.15$ GHz, $f_p = 72.31$ GHz, and $T = 2.96$ K. The indications on the right-hand side are the measured *Y* deflections used for gain and noise temperature calibration. T_0, T_N and T_R are equivalent noise temperatures of the room-temperature termination (300 K), the ignited noise tube (12 660 K), and the receiver, respectively. The inset shows a sketch of the temperature-stabilized part of the experimental setup.

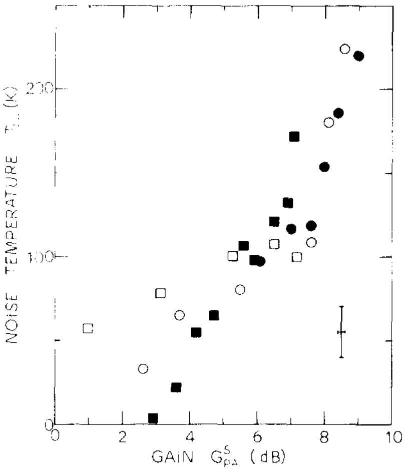

FIG. 2. Noise temperature T_{PA} versus gain G^s_{PA} as measured by varying only one parameter at a time. Different symbols are used for each parameter: dc bias current (open squares), signal frequency (full squares), pump power (open circles), and temperature (full circles).

sum of the receiver noise and the powers received in the signal and image bands of width B_{SA}. Application of two known broadband noise signals (noise tube on-off) yields an absolute calibration in equivalent noise temperature. The inferred DSB noise figure of the receiver including isolators, filter, and switch was 6.7 dB (corresponding to a SSB noise temperature $T_R \simeq 2160$ K).

The measured equivalent noise temperature T'_B may be expressed as

$$2T'_B = 2T_{WG} + [(G^s_{PA} + G^i_{PA})T_{2,\text{in}} + G^s_{PA}T_{PA} + g^a T_{2,\text{in}}]/L_{23}\,L_0, \qquad (1)$$

where T_{WG} is the effective noise temperature of the radiation from the output waveguide with attenuation L_0 (2, 35 dB), T_{PA} is the noise temperature of the parametric amplifier, G^s_{PA} is the signal gain, and G^i_{PA} is the idler-to-signal conversion gain. $T_{2,\text{in}}$ is the input noise temperature at port 2 of the circulator (c.f. Fig. 1) and g^a is the power reflection coefficient in the image band.

When the parametric amplifier is in a passive state or is replaced by a short circuit, the equivalent noise temperature becomes

$$2T''_B = 2T_{WG} + (T_{2,\text{in}}/L_{23}\,L_0)(g^s + g^a), \qquad (2)$$

where g^s is the power reflection coefficient in the signal band. With a short circuit at port 2, $g^s = 1$, whereas we measured $g^s \simeq 0.3$ (~ -5 dB) when port 2 was teminated by the amplifier stage in a passive state. Experimentally, it was found that $g^a = 1$, such that $g^s + g^a = 2$ and $g^s + g^a \simeq 1.3$ for the short and the passive amplifier stage, respectively. In both cases $2T''_B = 210 \pm 5$ K was measured implying that the second term in Eq. (2) is insignificant ($0.7T_{2,in}/L_{23}L_0 \lesssim 5$ K) within our experimental accuracy. This is consistent with an estimated input noise temperature $T_{2,\text{in}} \simeq 300$ K$/L_A$ + 300 K$/L_{32} \simeq 11$ K ($L_A = 18$ dB, $L_{32} = 17$ dB). Noise sources found to contribute less than 5 K have been neglected.

The particular junction reported on here has a normal-state resistance of 10.4 Ω and an extrapolated critical current at $T = 0$ K of 105 A/cm^2, corresponding to a maximum plasma frequency of 62 GHz. Figure 1 shows the received power as a function of dc bias current. The maximum plasma frequency at the experimental temperature was approximately 5% above the signal frequency. Also shown is a tracing of the noise background recorded with the spectrum analyzer window ~ 1 MHz from the signal line $(2T'_B + T_R)$. The recorder deflections used for gain and noise temperature calibration obtained with the switch directed towards the receiver are also shown. The maximum gain found here was 7.2 dB with a noise temperature $T_{PA} = 100 \pm 15$ K.

In Fig. 2 the noise temperature is plotted versus gain. The noise temperature is an increasing function of gain, rather independent of whether the change in gain is due to a change in dc bias current, temperature, or pump power level. This is an important experimental result not previously reported. In the case of low T_{PA} the received signal and idler powers were almost equal.

Normally positive gain was observed as a single symmetric peak with maximum at $\frac{1}{2}f_p$. However, depending on the setting of the tuning pins this peak may split up. In this case the frequency display of the individual peaks became asymmetric, as shown in Fig. 3. Here, the maximum gain is 7.1 dB and the 3-dB bandwidth is 17 MHz. T_{PA} is seen to increase significantly when f_s is tuned away from $\frac{1}{2}f_p$. Although this curve illustrates a rather special case, we have never observed a 3-dB bandwidth exceeding 20 MHz. The reason for this is not yet clear.

The amplifier operated at a given set of bias parameters was very stable and linear in signal power over a range of 10 dB with a 1-dB compression point 14 dB above the background noise level, $2\,T''_B + T_R \sim 10^{-14}$ W.[8]

Also the noise saturation of the amplifier was investigated. With the noise tube ignited the input noise temperature $T_{2,\text{in}}$ increased to 113 K. This reduced G^s_{PA} from 7.2 to 3.1 dB. T_{PA}, however, remained essentially unchanged (110 ± 15 K).

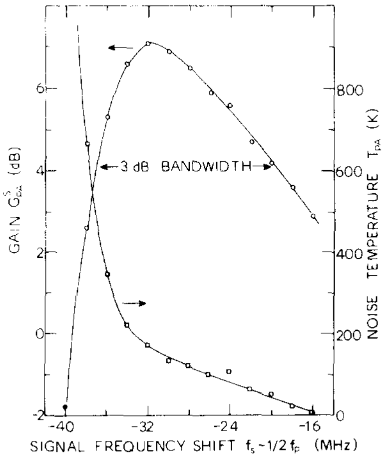

FIG. 3. Gain G^s_{PA} and noise temperature T_{PA} versus signal frequency with fixed dc bias current. Other parameters as in Fig. 1.

The dependence of the gain on the pump power level was measured. With increasing pump power P the gain first increased approximately linearly ($\Delta G^s_{PA}/\Delta P \simeq 3$ dB/1 dB) towards a maximum level, whereas T_{PA} continued to increase.

As shown in Fig. 1, the amplifier can conveniently be tuned at constant temperature by varying the dc bias current. However, when biased at constant current a strong temperature dependence of the critical current may cause both G^s_{PA} and T_{PA} to be sensitive to temperature variations. In the present case we observed that a 15 mK temperature change with all other parameters fixed produced a change in G^s_{PA} from 6 to 9 dB and a simultaneous change in T_{PA} from 100 to 200 K. Throughout the experiments the suppression of the critical current caused by the pump power was less than 1%.

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Superconducting properties of *in situ* formed Cu-V_3Ga composites

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Cu-V_3Ga composites were prepared from *in situ* formed multifilamentary Cu-V wires containing 20 vol.% of vanadium filaments. The highest value of the upper critical field at 4.2 K of the reacted composites was found to be 22.4 T, with a corresponding midpoint superconducting transition of 15.5 K. The overall critical-current density compares favorably with commercial V_3Ga composites over the entire field range (2×10^5 A/cm^2 at 4 T, 10^4 A/cm^2 at 18 T).

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Out of many high-temperature and high-field superconducting materials, only two (Nb_3Sn and V_3Ga) are currently being developed as practical multifilamentary composites. The A15 structure and the intrinsic properties of these two intermetallic compounds are well understood and are in many respects quite similar.[1,2] Although V_3Ga has a lower transition temperature T_c than Nb_3Sn, its superior current-carrying capacity at high fields (> 10 T)[3–5] makes it attractive for those applications where achieving high magnetic fields is of crucial importance.

In spite of the efforts to optimize the performance of practical superconductors, neither Nb_3Sn- nor V_3Ga-based composites have so far lived up to their expectations. V_3Ga composites, in particular, exhibit relatively low critical-current densities at low fields,[2] and both materials, because of their brittle nature, suffer from pronounced stress and/or strain sensitivity, leading to an irreversible degradation of critical-current density J_c. These and other problems arising primarily from difficulties in materials processing stimulated development of various techniques for *in situ* formation of superconducting filaments. Since the early work on Cu-Nb-Sn composites,[6] a number of authors[7–10] demonstrated that the critical-current density in these composites is comparable to that of conventional conductors. In addition, the original reports of their superior mechanical behavior[7] and have been confirmed by other investigators[11,12] and have been shown to be a common characteristic of the ultrafine filamentary composites.[13]

In contrast to the rather extensive efforts to develop Cu-Nb and Cu-Nb-Sn *in situ* composites, only one attempt to produce Cu-V-Ga filamentary composites by the *in situ* approach has been reported in the literature.[14] The critical-current densities in a variety of composites prepared under different experimental conditions (Fig. 1) were somewhat inferior to conventional Cu-V_3Ga conductors. Similarly, the superconducting transition temperatures were found to be 2–3 K lower than values reported for bulk V_3Ga compounds.[15]

We have recently reassessed the factors which govern the formation of V_3Ga compounds and concluded that there are no intrinsic reasons to prevent the fabrication of high-quality Cu-V_3Ga composites by the *in situ* approach. Our preliminary results, reported in this paper, demonstrate that the critical temperature T_c and the upper critical field H_{c2} of *in situ* conductors can be as high as the best values reported for bulk V_3Ga. Their transport properties are comparable to those of the conventional composites, and, furthermore,

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