Noise Bolometer for Terahertz Waves

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***Abstract*—An advantage of superconducting detectors is a much lower noise in comparison to their semiconductor counterparts. We have studied the magnitude and spectrum of electric noise in thin superconducting NbN nanostrips carrying a subcritical current. Analysis of the experimental data suggests that the noise appears due to fluctuations in the two-dimensional vortex gas below the Kosterlitz-Thouless phase transition. Implementing this approach to the noise mechanism, we proposed a novel detector. The novelty is the use of the noise, which generally hampers the performance of conventional detectors, as the physical quantity that itself senses radiation. Our detector patterned from a thin NbN superconducting film and integrated in a planar log-periodic antenna. The detector operates at 4.2 K in the current-carrying superconducting state. Optically measured noise-equivalent power amounted at 10^{-13} W / Hz$^{1/2}$ and is likely to improve at lower temperatures.**

***Index Terms*—Noise in superconductors, nonequilibrium superconductivity, Superconducting terahertz and submillimeter wave detectors.**

I. Introduction

THERE have been several superconductor detector technologies for THz-frequency range successively developed during the last decade. Transition edge microbolometers [1] working at millikelvin temperatures provide a lowest noise equivalent power (NEP) of 10^{-18} W/Hz$^{1/2}$ along with the 100-millisecond time constant. Hot-electron detectors [2], although less sensitive, are much faster since their response is controlled by electron-phonon interaction. The strength of this interaction and, consequently, the response time, can be varied [3] via controllable disorder. Superconducting kinetic inductance detectors [4] are supposed to achieve background limited NEP if they would operate at a very low temperature with a low-noise SQUID pre-amplifier. Superconductor-Insulator-Superconductor (SIS) and Normal (metal)-Insulator-Superconductor (NIS) direct detectors have been also proposed. A noise equivalent power of 10^{-15} W/Hz$^{1/2}$ at 4 K [5] and 10^{-17}-10^{-18} W/Hz$^{-1/2}$ at 100 mK [6] was estimated for SIS and NIS direct detectors, respectively. For all these sensors, an electrical noise of any type hampers the ability of a sensor to detect radiation. In an ideal detector, fluctuations of the background radiation dominate over other noise sources. In practice, the detector itself and a pre-amplifier generate at least a part of the noise. A concept of the noise bolometer has been recently proposed [7] in that a detector senses radiation via radiation induced changes of its own electrical noise. Somewhat analogous, a temperature dependence of the fundamental Johnson noise has been used [8] for thermometry.

In this paper we present experimental evaluation of a noise bolometer and estimate its ultimate performance.

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II. Detector Design and Experiment

The detector is a 80 nm wide meander line made from a 5 nm thin superconducting NbN film (as shown in Fig. 1). It operates deep in the superconducting state and carries a supercurrent slightly less than the critical current. Radiation couples with the detector via an immersion lens and a planar log-periodic antenna, which jointly define the useful spectral range from 1 to 5 THz. The current RF noise was recorded at a frequency of 3 GHz in a hundred megahertz band. The noise equivalent power was evaluated for the signal produced by alternating thermal loads (300 & 77 K) at the detector input. At an ambient temperature of 4.2 K measured noise-equivalent power amounted at $\approx 10^{-13}$ W/Hz$^{1/2}$ while a time-constant of approximately 250 ps was anticipated.

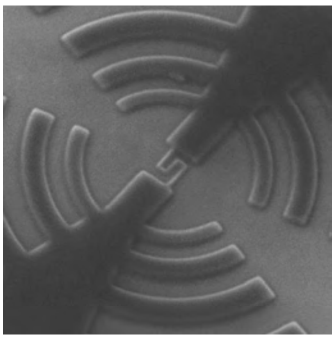

Fig. 1. Microphotograph of the NbN meander line incorporated into the planar log-periodic antenna.

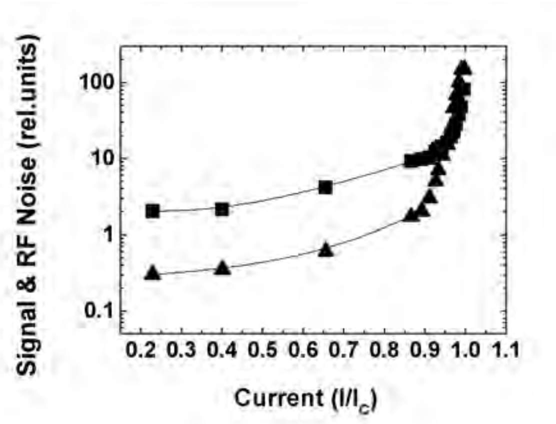

Fig. 2. RF noise (squares) and the signal (triangles) as function of the bias current. Both measured at 4 K.

The sensitivity of the detector is limited by statistical variations of the noise power. Assuming that the time variations of the spectral power density are totally uncorrelated, the dispersion of the noise power can be found with the radiometric equation as $\delta P_\omega \approx P_\omega(B\, t_0)^{-1/2}$ where P_ω is the mean value, t_0 is the integration time and B the bandwidth. The noise equivalent power for the detector is then $NEP = \delta P_\omega/(dP_\omega/dW)$ where W denotes the radiation power at the detector input. Fig 2 shows the signal due to alternating hot/cold load and the mean RF noise power as function of the bias current. Both the signal and the noise demonstrate similar variation resulting in a practically frequency independent noise equivalent power.

III. Noise Appearance & Mechanisms

Noise of a superconducting current-biased meander appears as a sequence of random voltage pulses. When measured with a broad-band microwave amplifiers in series with a band-pass filter, it causes additional microwave power. If measured with an integrating low frequency voltmeter, the noise causes a non-zero dc voltage over the nominally superconducting structure. The shape of the superconducting transition and the current and temperature dependence of the noise pulse rate in our meanders are best understood when fluctuations in the gas of magnetic vortices are taken into account [9]. Below the two-dimensional Kosterlitz-Thouless transition, almost all vortices are bundled into vortex-antivortex pairs. The binding energy of a pair depends on its orientation with respect to the current and has a current dependent minimum value E_{VP}. The process of unbinding can be seen as a thermal excitation across this energy. Free partners of a vortex-antivortex pair are driven apart by the Lorentz force F_L exerted by the bias current (Fig. 3). Vortex motion (even over a distance smaller than the strip width) produces a change in the superconducting phase difference between the strip ends and, consequently, a voltage pulse. The rate of these events is proportional to the thermodynamic probability of pair

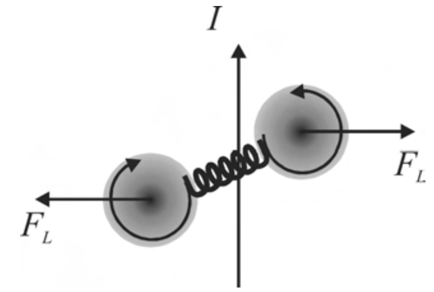

Fig. 3. Schematics of the current-induced unbinding of a vortex-antivortex pair. Unbinding force peaks when the pair is oriented normal to the current.

unbinding and depends on the fractional bias current I/I_C and material parameters A as

$$N \propto \exp\left(-\frac{E_{VP}}{k_B T}\right) \propto \left(\frac{I}{I_C}\right)^A ; \quad E_{VP} \approx A \ln\left(\frac{I_C}{I}\right)$$

It has been shown in [7] that, due to an exponential temperature dependence of the recombination time, NEP of the detector using this noise mechanism should scale as $T\exp(\Delta/k_B T)$. Estimates for our NbN detector show that NEP can reach 10^{-18} W·Hz$^{-1/2}$ at 0.3 K. Preliminary data on the temperature dependence of the noise support the expectations.

IV. Conclusion

In comparison to relatively slow low temperature detectors, an obvious benefit of our detector approach is that the $1/f$ noise is not present in the high-frequency readout. Another practical advantage of the use of the current noise is that it dramatically increases with the bias current making it possible to substitute a complicated SQUID readout with less sensitive and cheaper microwave amplifiers.

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