KINETIC INDUCTANCE THZ MIXER FOR SPACE APPLICATIONS

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We consider a new type of hot-electron mixer that employs a kinetic-inductance response in a superconducting film near superconducting transition. The significant advantage of this mixer over the resistive one is that the intermediate frequency bandwidth and the local oscillator power can be adjusted independently. The intermediate frequency bandwidth is determined by the inverse quasiparticles multiplication time. The local oscillator power is determined by the electron cooling time, which is the electron-phonon relaxation time for phonon-cooled mixers. Our modeling has shown that the intermediate frequency bandwidth can be as large as 50 GHz along with the local oscillator power of about 10 nW and the conversion efficiency ~ 0.01.

Currently, hot-electron superconducting bolometer (HEB) mixers are the most sensitive heterodyne detectors at THz frequencies. Both the diffusion and the phonon cooled HEB mixers demonstrate very good noise characteristics [1,2]. The achieved noise temperature in practical mixers is approximately 10 times higher than the quantum limit, $T_Q = h\nu/k_B$. The intermediate frequency (IF) bandwidth, B_{IF}, is given by the inverse electron cooling time, τ_c, i.e., $B_{IF} = 1/(2\pi\tau_c)$. The maximum IF bandwidth of ~ 9 GHz has been demonstrated in an ultrashort diffusion-cooled Nb mixer [3]. The local oscillator (LO) power of an HEB mixer is $P_{LO} \approx C_e T_c/\tau_c \propto T_c^2/\tau_c$, where C_e is the electron heat capacity. Typical low values for the LO power are in the range 20-100 nW [3]. A further decrease of the LO power in HEB mixers can be achieved by using superconductors with lower critical temperature [4].

In the current work, we analyze a new type of hot-electron mixer, which employs a kinetic-inductance response in a superconducting film in the vicinity of the superconducting transition. This mixer allows for substantial increase of the IF bandwidth and simultaneous decrease of the LO power.

The kinetic inductance response to the electromagnetic radiation near the superconducting transition has been studied in many works [5,6,7,8]. The radiation

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quanta create large number of excited quasiparticles in a superconducitng film. Electron-electron scattering ensures effective avalanche-like multiplication of photoexcited quasiparticles. Increase of the number of quasiparticles (decrease of the number of Cooper pairs) leads to a change of kinetic inductance which can be detected via a change of the ac voltage across the current biased superconducting bridge. In impure superconductors, the electron-electron scattering time, τ_{ee}, is significantly shorter than the electron-phonon time, $\tau_{e\text{-}ph}$, and on the time scale longer than τ_{ee} one can describe the electron kinetics by the electron temperature, θ, in the same way as in the resistive state:

$$\delta\theta = \frac{P}{C_e}\frac{\tau_{e-ph}}{1+i\omega\tau_{e-ph}}\exp(i\omega t), \tag{1}$$

where P is the electromagnetic power absorbed in a superconducting bridge.

The kinetic inductance, L_k, is a function of the electron temperature, so the responsivity of the kinetic-inductance detector may be presented as

$$S_\omega = I\frac{\partial L_k}{\partial\theta}\frac{\omega\theta_\omega}{P_\omega} = \frac{I}{C_e}\frac{\partial L_k}{\partial\theta}\frac{i\omega\tau_{e-ph}}{1+i\omega\tau_{e-ph}}, \tag{2}$$

where I is the biased current, and ω is the modulation frequency; the subscript ω denotes the corresponding Fourier component.

In general, the dependence of the responsivity on the modulation frequency has a shape shown in Fig. 1. At low frequencies, the inductive signal is proportional to the frequency. Then, at $\tau_{e\text{-}ph}^{-1} < \omega < \tau_{ee}^{-1}$ the frequency dependence has a plateau, which can be used for mixing. At higher frequencies, a $1/\omega$ decrease of the signal with frequency is expected. Here, the variations of the electromagnetic field are so fast that the quasiparticle multiplication cannot follow and, as a result, the kinetic inductance does not change much. Experiment [8] has demonstrated the presence of the linear and the frequency independent parts of the dependence $S_\omega(\omega)$. The high-frequency region above τ_{ee}^{-1} could not be observed in view of instrumentation bandwidth limitation.

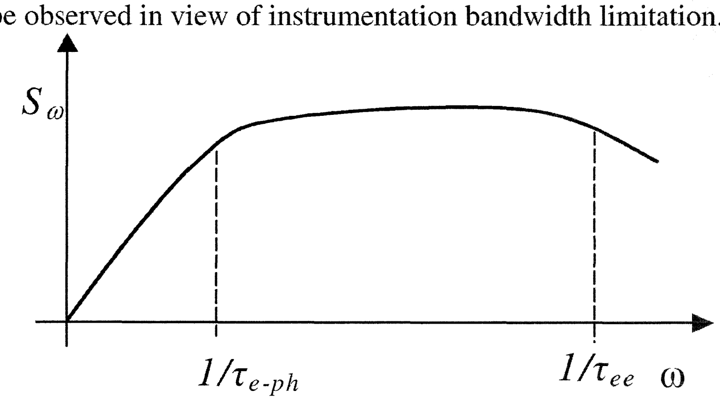

Fig. 1. Dependence of the responsivity on the modulation frequency

The electron-electron scattering rate in an impure superconductor near the transition is given by [9]:

$$\frac{1}{\tau_{ee}} = \frac{e^2 R_\square T_c}{2\pi\hbar^2}\ln\left(\frac{\pi h}{e^2 R_\square}\right), \tag{3}$$

where $R_{\square}$ is the sheet resistance. Typical values of τ_{ee} in disordered films at helium temperatures are 2-7 ps. Thus, the kinetic-inductance mixer would allow for an IF bandwidth

$$B_{IF} = 1/(2\pi\tau_{ee}) \simeq 50 \text{ GHz}. \qquad (4)$$

For the proposed kinetic inductance mixer, the IF bandwidth and the LO power are controlled by different electron processes and do not have to be traded off. In order to minimize the LO power, the mixer should work in the phonon-cooled mode. Then, the LO power will be given by :

$$P_{LO} \cong C_e T_c / n\tau_{e-ph}, \qquad (5)$$

where n=4-6 is the exponent in the temperature dependence in the electron energy loss function. Choosing the volume of the superconducting bridge, one can adjust the LO power to a required value. For example, for Nb bridge of 10nm×0.1μm×1μm and T_c= 5.5K the LO power is expected to be ~10nW.

Let us now consider the responsivity near the superconducting transition. In this region the temperature dependence of the kinetic inductance is [10]

$$L_K = \frac{2\hbar R k_B T}{\pi(\Delta(T))^2} \propto (1-T/T_c)^{-1}, \qquad (6)$$

where $\Delta(T)$ is the superconducting gap, and R is the normal state resistance. The kinetic-inductance response is proportional to the biased current, which is limited by the critical Ginzburg-Landau current,

$$I_{GL} = \frac{8\sqrt{2\pi^5}}{21\sqrt{3}\,\varsigma(3)} \frac{(k_B T)^{3/2}}{(\hbar D)^{1/2}} \frac{L}{eR} (1-T/T_c)^{3/2}, \qquad (7)$$

where D is the diffusion coefficient, and L is the length of the bridge.

Assuming that the biased current is a times smaller than the critical current and combining Eqs. 2, 6 and 7, we obtain the responsivity

$$S \approx \frac{0.1}{a} \frac{(\hbar D)^{1/2}}{(k_B T)^{3/2}} \frac{eR}{L} (1-T/T_c)^{-1/2}. \qquad (8)$$

Choosing a = 2 and $(1\text{-}T/T_c)^{-1/2}$ = 6, for a 10nm thick and 0.1μm wide superconducting Nb bridge with T_c = 5.5K, resistivity of 5×10^{-5} Ω cm, and the diffusion constant D = 1 cm^2/s, we get the responsivity of $5\cdot10^3$ A^{-1}.

The mixer conversion efficiency is given by

$$\eta = \frac{2S^2 P_{LO}}{R_L}, \qquad (9)$$

where R_L = 50 Ω is the IF load resistance. With S = 5000 A^{-1} and P_{LO} = 10nW, we expect the conversion efficiency to be of the order of 10^{-2}. With a typical LHe cooled HEMT amplifier (noise temperature 2-5 K) the mixer noise temperature of several hundred Kelvin can be expected.

In summary, we propose a new type of low-noise hot-electron mixer based on the kinetic-inductance response in the superconducting state. The IF bandwidth of this mixer is given by the rate of the electron-electron scattering processes and it can be as large as 50 GHz. The LO power is independently controlled by a relatively slow electron cooling process and can be separately adjusted to the required low values.

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