Microwave nonlinear effects in He-cooled superconducting microstrip resonators

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Abstract

Nonlinear phenomena in superconducting niobium microstrip resonators filled by liquid helium are studied in microwaves. The found nonlinear resonance is explained by thermally induced variations of the helium dielectric permittivity caused by the microwave power losses in superconductor. A number of interesting manifestations of this thermal instability have been observed including the parametric pulse generation of the monochromatic microwave signal, generation of acoustic pulses.

Key words: superconductor; microwave; helium; nonlinearity; thermal instability

Thermal nonlinearity is one of the main limitations to achieve reliably high quality in superconducting microwave resonators. In future applications of superconducting resonators a problem of heat sinking by liquid helium may be significant. In this connection we studied thermally induced nonlinear phenomena in superconducting niobium microstrip resonators filled by liquid helium.

Measurements were done in the half-wave mode of symmetric microstrip resonator at 8 GHz, which consists of niobium foil with a thickness of 15 μm sandwiched between two dielectric disks. The $\lambda/2$ strip together with gap coupling microstrip transmission lines were assembled inside a cylindrical Nb cavity to form a shielded microstrip resonator. Critical temperatures of superconducting niobium materials were of 9.2 K. The assembly was mounted in the helium bath of a cryostat. Sapphire or teflon with relative dielectric constants of 10 and 2, respectively, were used as the dielectric laminae of a microstrip resonator. The residual volume of a resonant cavity was full of helium. An C4-27 spectrum analyser was used to measure the microwave transmission spectra. A 10 mW klystron generator Γ4-83 or an BWT sweep-generator PK2-28 were used as a microwave input power source. To investigate the transient behaviours, the output power was measured as a function of time without changing the cavity arrangement.

The primary manifestations of resonator nonlinearity are reduction in Q, a shift in resonant frequency and an asymmetry of resonance curve. It can be seen in Figs. 1a to 1d that measured resonators exhibit highly nonlinear behaviour at input power levels exceeding tenths of mW. The nonlinearity is revealed as asymmetry of the resonance curve during the slow sweep of a frequency. Moreover, a shape of the asymmetric resonance curve depends on the frequency-sweep direction. The found in Fig. 1 nonlinear behaviour is provided by the fact that a resonant frequency f_p depends on the liquid helium dielectric permittivity ϵ_{He}. As a result it should depend on temperature.

The microwave power losses per unit area of the superconductor surface are estimated as $P \cong R_{HF}H^2/2$, where R_{HF} is the surface resistance of superconductor, H is the amplitude of magnetic field at the surface of superconductor. This heat flux has to be conducted through the niobium and helium in resonator cavity to be removed by the helium bath of cryostat. That is described by the equation of thermal conductivity ΔQ=kΔT=k$(T - T_0)$, where T is the temperature of

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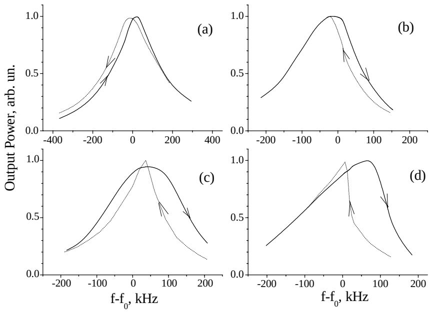

Fig. 1. Transmitted power versus frequency increment $f - f_0$ for different resonance frequency f_0 (8.6 GHz for a and 7.9 GHz for b-d) and helium bath temperature between 4.28 K and 4.31 K measured for both up (solid line) and down (dotted line) frequency sweeps with different sweeping rates characterised by the time derivative of $\xi = (f - f_0)/f_0$. Following inequalities are held: $|\xi_t'|_a > |\xi_t'|_b > |\xi_t'|_c > |\xi_t'|_d$.

liquid helium near the surface of superconductor, T_0 is the helium bath temperature, k is the effective thermal conductivity. Since k has a finite value, heating of liquid helium layer adjacent to the superconductor surface is possible. Helium heating should change the resonant frequency of microstrip resonator because of the temperature variation of ϵ_{He} helium permittivity: $\epsilon_{He} \cong -\beta \mathrm{T} + \gamma$, where β and γ are the positive constants. Since the inverse square of the resonant frequency can be written as $f_p^{-2} \cong f_0^{-2}(1 + c_1\epsilon_{He})$, one can deduce in linear approximation

$$f_p^2 \cong f_0^2(1 - c_1\gamma + c_1\beta T_0 + \frac{c_1\beta R_{HF}}{2k} H^2). \qquad (1)$$

Since the resonant frequency increases with rise of the H, the resonance curve bends to the higher frequencies as it is seen in Fig. 1d. A resonance curve dependence on the rate and direction of the microwave generator frequency sweep can be explained as follows. The resonant frequency increases with increasing temperature due to microwave losses. So if the input power frequency changes from lower to higher values, it will spend a longer time in the region of peak on the resonance curve than it will be in the alternative case. As a result the resonator will be heated stronger and its resonant frequency will increase up to the higher value during the generator frequency movement from down to up than it will be in the alternative case. Thus the results presented above indicate that the observed nonlinearity requires incorporation of the helium heating effects.

The pronounced hysteresis behaviour can be seen in Fig. 2a, in which the results are shown for very slow (manually) both up and down frequency sweeps. The quite narrow transmitted power transient pulse arises during frequency moving down. The kinetics of the ob-

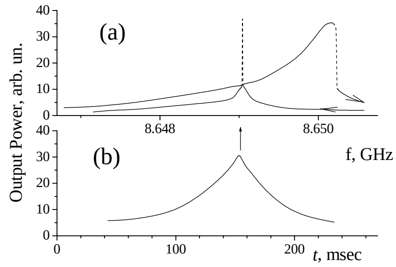

Fig. 2. a) Transmitted power versus frequency for the very slow (manually) both up and down changes of the generator frequency. Arrows show the frequency sweep direction. Solid lines correspond to steady state signal; dotted lines correspond to the unstable transient signal. b) Kinetics of the transmitted power pulse shown near the frequency 8.649 GHz in Fig. 2 a.

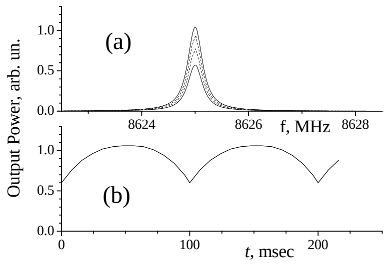

Fig. 3. a) Transmitted power versus frequency during the generation of the acoustic pulses. b) Kinetics of peak shown near the frequency 8.625 GHz in Fig. 3a.

served pulse is shown in Fig. 2b that demonstrates exponential growth and decay of the transmitted power. A value of lifetime of the exponential growth and decay was estimated as 30 msec. It should be noted that the measured value of a decay time in the case of linear resonance would correspond to the effective quality factor order of 2×10^9. We suppose that the exponential pulse generation of the monochromatic microwave signal can be explained by the parametric effect caused by thermally induced variations of the helium dielectric permittivity. The estimations show that the helium vapour bubble exponentially grows and disappears in the thin layer surrounding the niobium strip between teflon disks that results in the observed transient spike of the transmitted power. Moreover, during the helium vapour pumping especially at temperatures slightly above the temperature of λ-point (T=2.17 K) the generation of periodical (10 Hz) acoustic pulses was observed. Fig. 3 demonstrates the periodically varied intensity of the resonant peak during the generation of the acoustic pulses. From this figure we can conclude that the acoustic pulses correlate with the periodical variations of the resonator transmittivity.

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