Microscopic Tunnelling Model of Josepshon Flux-Flow Oscillator

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Flux-flow oscillator (FFO) [1] is a long Josephson junction where flux of Josephson vortices (fluxons) excite linear modes of electromagnetic waves. Typically length of a FFO is made considerably longer than the Josephson penetration length in order to accommodate a chain of fluxons. Because of its potential to be used as source of sub-mm electromagnetic waves [2], it has attracted a considerable attention of the scientific community [3].

Here we present numerical simulations of Josephson FFO with the use of the Werthamer microscopic tunnelling theory [4]. To our knowledge this is the first microscopic calculation of FFO dynamics which is done beyond the phenomenological RSJ model, apart from the single study of an isolated soliton in a long Josephson junction [5].

To simulate the dynamics of FFO we solve numerically the integro-differential equation

$$\ddot{\varphi} - \varphi_{xx} - \beta\dot{\varphi}_{xx} + j(t) = 0 \qquad (1)$$

where the tunnelling current $j(t)$,

$$j(t) = -\alpha_N\dot{\varphi} + \frac{k}{\Re j_p(0)}\int_0^\infty \left\{ j_p(kt')\,\sin\left[\frac{\varphi(t)+\varphi(t-t')}{2}\right] + \bar{j}_{qp}(kt')\,\sin\left[\frac{\varphi(t)-\varphi(t-t')}{2}\right]\right\} dt'$$

depends on the history of the ac electric fields in the junction and $\varphi(x,t)$ is the superconducting phase difference across the junction, $j_{qp}(t)$ and $j_p(t)$ are time-domain kernels describing quasiparticle and pair components of the tunnel current.

We employ the numerical scheme developed in [6] to solve the integro-differential equation (1). In this model, the Josephson self-coupling effect [4, 7, 8] is naturally captured by the microscopic tunnelling theory, without need to resort to existing phenomenological models [9].

Finally, we study FFOs of unconventional geometry [10] which exhibit peculiar chaotic behaviour. It has been shown in [11] that the conventional FFO shows chaotic dynamics in so called displaced linear slope (DLS) of the low-voltage region on the $I-V$ characteristics. As opposed to the conventional FFO, a modified FFO exhibits chaotic state at significantly higher voltages and in the most of its $I-V$ up to about half of the gap voltage. Therefore one may reach significantly higher power of chaotic signal with the use of such FFOs as compared to using the DLS region.

[1] T. Nagatsuma et al., J. Appl. Phys. 54, 3302 (1983); *ibid* 56, 3284 (1984); *ibid* 58, 441 (1985); *ibid* 63, 1130 (1988);

[2] V. P. Koshelets and S. V. Shitov, Supercond. Sci. Technol. 13, R53 (2000);

[3] V. P. Koshelets et al., IEEE Trans. Appl. Supercond. 17, 336 (2007); M. Yu. Torgashin et al., IEEE Trans. Appl. Supercond. 17, 339 (2007); M. Jaworski, Phys. Rev. B 81, 224517 (2010);

[4] N.R. Werthamer, Phys. Rev. 147, 255 (1966);

[5] N. Grønbech-Jensen, S. A. Hattel and M. R. Samuelsen, Phys. Rev. B 45, 12457 (1992).

[6] A. A. Odintsov, V. K. Semenov and A. B. Zorin, IEEE Trans. Magn. 23, 763 (1987).

[7] L.-E. Hasselberg, M.T. Levinsen, and M.R. Samuelsen, Phys. Rev. B, 1974, 9, 3757.

[8] V. P. Koshelets, S. V. Shitov, A. V. Shchukin, L. V. Filippenko, J. Mygind and A. V. Ustinov, Phys. Rev. B 56 5572 (1997).

[9] A. L. Pankratov et al., Phys. Rev. B 75, 184516 (2007); A. S. Sobolev et al., Physica C 435, 112 (2006). D. R. Gulevich et al., Nanosystems: Phys., Chem., Math. 4, 507 (2013).

[10] D. R. Gulevich and F. V. Kusmartsev, Phys. Rev. Lett. 97, 017004 (2006).

[11] A. V. Ustinov, H. Kohlstedt, and P. Henne, Phys. Rev. Lett. 77, 3617 (1996).