Active Josephson traveling wave antennae as prospective terahertz oscillators

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A terahertz superconducting oscillators based on large amount of Josephson junction embedded in open system guiding traveling electromagnetic wave is theoretically considered and computer simulated. It is shown that such active Josephson antennae represent oscillator effectively radiated into open space with power scaled with the system size and number of junctions. Dynamics and directivity patterns of such Josephson antennae depending on bias current is investigated and it is shown that such oscillator with sufficiently large junction amount can be competitive with quantum cascade lasers.

It is well known that the Josephson Effect can be used for the generation of high-frequency electromagnetic radiation. The frequency is limited only by the superconducting energy gap. For low-Tc superconductors the frequency is in the sub-THz range and for high-Tc superconductors it can be up to approximately 20 THz. But the emission power from a single Josephson junction is quite small. It can be considerably enhanced provided coherent contribution of many, $N \gg 1$, Josephson junctions to radiated electromagnetic field.. For achieving a practically important mW level of emission power very large arrays containing $N \sim 10^4 - 10^5$ Josephson junctions would be needed. Taking into account the attainable integration density, such arrays would have a typical size of $L \sim 1$ cm, which is significantly larger than the wavelength λ even at sub-THz frequencies.

The larger the array is the more difficult is the synchronization. This is caused by large phase delays along the array. Recently, it was suggested [1] that the synchronization of extremely large arrays can be mediated by a unidirectional traveling wave along the array, qualitatively similar to the operation of a traveling wave Beverage-type antenna [2].

In this work, we consider such large-size Josephson systems and present their theoretical description and computer simulation. We demonstrate that in some classes of such systems, traveling-wave regimes are possible, under which all Josephson junctions are under identical electrodynamic conditions and make coherent contributions to the radiation field. Such systems, which will be called active Josephson traveling wave antennas, are scalable, i.e., in the case of optimal matching, the intensity of their radiation increases in proportion to the size of the system or the number of the Josephson junctions. An important component, which ensures coherence of the contributions made by a great number of junctions, is the lateral energy leakage from the transmission line (vertical radiation output), which prevents saturation of the nonlinearity of individual junctions with narrow dynamic ranges. Such systems can be used as a basis for Josephson oscillators producing power levels sufficient for practical applications. A simple qualitative theory of open Josephson traveling-wave lines was developed and conditions for existence and stability of travelling wave regimes were found [1].

If there exists the traveling wave of current along Josephson array with wave number h it will radiate electromagnetic wave to open space at an angle $\alpha = \sin^{-1} h/k$, where k is the wave number of the emitted wave in vacuum and α counted from normal to substrate. For $h/k < 1$ when current wave is faster than speed of light in vacuum it is an ordinary transverse electromagnetic wave, for homogeneous current with $h = 0$ the radiation will be directed strictly vertical. But for $h/k < 1$ when current wave is slow the angle α is imaginary and the traveling electromagnetic wave turns to a surface plasmon traveling along the interface of the wafer and radiated from the edge of structure.

It should be noted that due to not perfect matching conditions at edges of array the traveling wave would not be pure traveling and some mixture of opposite propagating wave will always be presented. But Standing Wave Ratio (SWR) should be final to provide the absence of AC field nodes so that all junctions will be pumped by common field. Since the AC current distribution and radiated field defined by cooperative dynamics of Josephson junctions should be found self consistently we undertook direct computer simulations of such active Josephson antennae.

A numerical simulation code based on the Finite Difference Time Domain (FDTD) method and a self-consistent solution of the nonlinear equations which describe the Josephson junctions has been developed. The results of simulation of some variants of Josephson traveling-wave antennas with different radiation patterns are presented.

An example chosen for the calculations is a Josephson system similar to the two folded wire traveling-wave antenna. The simulated Josephson system is a set of thin perfect conductors, lumped linear elements, such as capacitors, inductances, resistors, and sources of DC electromotive forces, and nonlinear active elements, Josephson junctions simulated by resistively and capacitive shunted model. These elements are located on the surface of a dielectric plate and interact via the electromagnetic field in the surrounding space. Calculations start from an initial distribution for Josephson phases and electric and magnetic fields on the computational grid and continue until a stationary state is reached. After that time average values of voltages and currents in Josephson junctions and Fourier amplitudes of the fields around the sample are

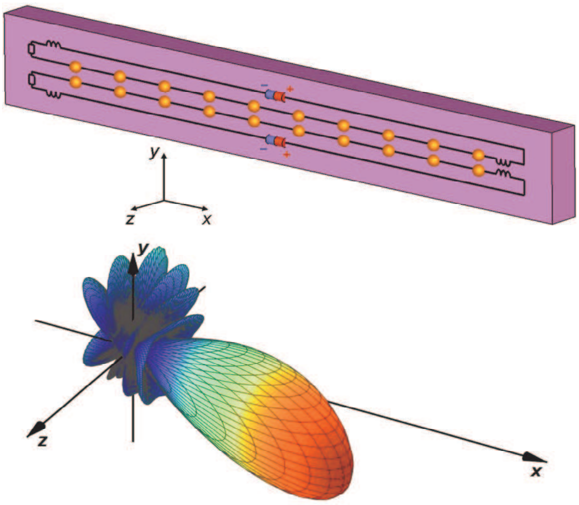

Fig. 1. Appearance and directivity pattern of two folded Josephson active antenna with separate DC bias demonstrating oblique angle radiation due to junction synchronization with fast traveling current wave. Yellow circles denote Josephson junctions, bias battery, resistor and inductances, serving for matching are denoted as usual.

obtained. The radiation pattern at a fixed frequency is calculated using a standard near-to-far field transformation [3]. Full power of emission was calculated by integration of the far field Pointing vector. Examples of such systems representing an antenna containing a set of straight and broken wires with different number of Josephson junctions imbedded into together with radiation patterns generated by them are shown on Fig. 1-3. The pictures shown demonstrate various regimes of radiation manifested itself by different radiation patterns which strongly depend on geometry of antennae and DC bias. When bias increases the oscillation frequency defined by Josephson relation $\hbar\omega = 2eV$ also increases, mode spectrum enriches and directivity patterns became more complicated. As it is common for oversized radiating system to control generation regimes and directivity pattern some complication of the system to provide working mode selection is needed. This work is now underway.

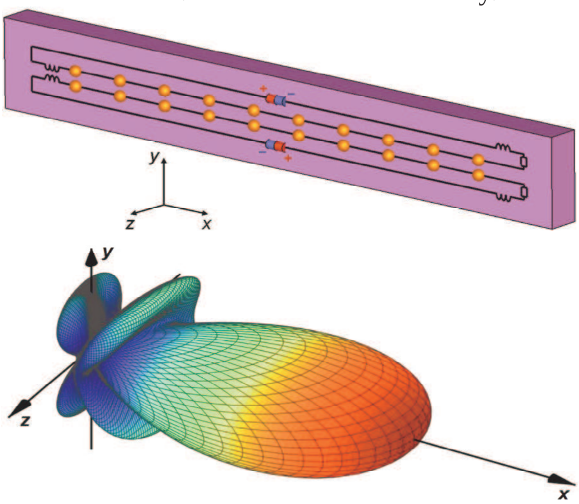

Fig. 2. The same Josephson active antenna as in Fig. 1 but radiated along the wafer due to synchronization with slow current wave.

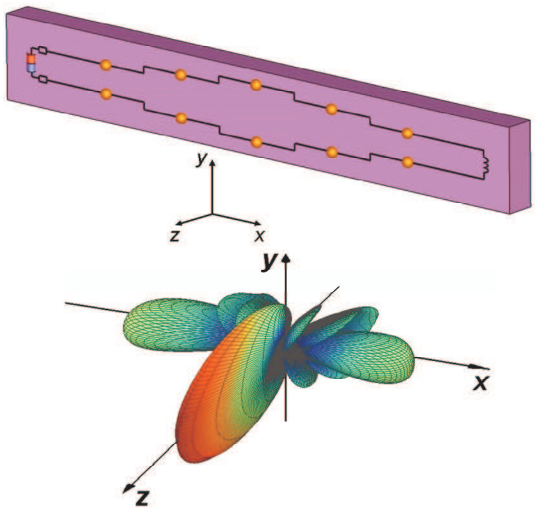

Fig. 3. Appearance and directivity pattern of Josephson active antenna consisting of two broken lines with common DC bias. It I seen pronounced lobe corresponding to vertical output of radiation due to junction synchronization with homogeneous mode of substrate.

Dependence of power of radiation and behavior of spectral properties of radiation on junction number, current and voltage spectra on individual junctions support suggested concept of array synchronization by traveling wave.

Recently [4] Josephson emission from such larger-than-the-wavelength Nb-NbSi-Nb junction arrays consisting of order 10^4 junctions was investigated experimentally and angular dependence of radiated energy was measured by small InSb semiconductor detector. The asymmetry of radiation pattern that was found support the suggested our concept of synchronization mediated by traveling wave. We argue that such a mechanism of synchronization opens a possibility for phase locking of very large arrays of oscillators what opens a way to develop effective Josephson oscillator of Terahertz range.

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