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論 文 の 内 容 の 要 旨

Electromagnetic (EM) waves in the terahertz (THz) frequency band have many important applications, such as DNA diagnosis, telecommunication and materials characterization. Nevertheless, they are difficult to generate by either electronic or photonic technique. To develop strong and compact solid-state source of THz EM wave is a big challenge.

A Josephson junction is a natural dc-to-ac converter. As Cooper pairs tunnel back and forth across the junction under a dc bias voltage, Josephson plasma oscillations are excited, which then radiate a part of the energy into space in the form of EM wave. The radiation frequency and the bias voltage follow the ac Josephson relation; quantitatively, a bias voltage of 1 meV corresponds to 0.483 THz. However, the radiation power from a single junction is too small for practical applications and the frequency is around 100GHz limited by the small superconducting energy gap.

The discovery of the intrinsic Josephson effect in cuprate high-Tc superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), provides a possibility to develop strong sources of THz EM waves. Due to the layered structure of crystal the superconductivity is strongly modulated along the c axis, and thus a BSCCO single crystal forms a stack of intrinsic Josephson junctions (IJJs). The advantages of IJJs are: 1) the superconductivity gap is about 60 meV which supports operating frequency as high as 10THz without severe damping; 2) all junctions are almost identical; 3) there is a huge coupling between junctions because of the atomic thickness of individual junction. Therefore, BSCCO is an ideal material for generating THz EM wave.

An experimental breakthrough was achieved in 2007 when scientists successfully observed coherent emissions from a rectangular mesa mounted on the top of a substrate of BSCCO single crystal under a c-axis voltage bias. It is revealed experimentally that a coherent emission takes place at the bias voltage when the frequency determined by the ac Josephson relation equals the fundamental cavity mode, corresponding to a half wavelength of the Josephson plasma in the mesa. This new experiment challenged our understanding on the physics of stacked Josephson junctions, since all the known states in IJJs so far could not explain the novel experimental results.

In order to understand the electrodynamicis of the system, it is important to explore the dynamics of superconductivity phase in the coupled Josephson junctions. In the present study, theoretical investigations on the inductively coupled sine-Gordon equations for the gauge-invariant phase differences in IJJs have been performed. For a mesa with thickness of ~1 μm used in the recent experiments, there exists a significant impedance mismatch at the junction edges. As a good approximation, the boundary condition for the gauge-invariant phase difference should be of Neumann type. Solving the coupled sine-Gordon equations under the Neumann boundary condition. a novel π kink state was discovered. In this state the total phase consists of the following three parts: (1) a term lineally proportional to time caused by the bias voltage according to the ac Jpsephson relation. uniform both in the c axis and the lateral direction, (2) a static phase term with alternating lateral variations in neighboring junctions, and (3) the cavity plasma term uniform along the c axis. For the fundamental cavity mode of a rectangular mesa. the static phase term runs sharply from 0 to π at the center of the mesa in one junction. forming the π phase kink, arid to –π in the next junction. forming the –π phase kink.

The π phase kinks couple the cavity plasma and the dc driving current. which enhances significantly the plasma oscillation when the bias voltage is tuned to the value corresponding to cavity frequency. The strong plasma oscillation induces large dc supercurrent due to the nonlinearity of the dc Josephson relation, namely the supercurrent is proportional to the sinusoidal function of the phase diflference, When a large amount of the dc power is pumped into the plasma oscillation at the cavity resonances, a part of the energy is radiated from the edge of junctions into the space. The maximum radiation power is estimated to be 10mW from a mesa of length of 300 μm and thickness of 1 μm with efficiency ~10%. The working frequency is 0.5~2 THz.

To verify the π kink state experimentally, one needs to determine the boundary condition of the IJJs. For a rectangular mesa. however, the frequency corresponding to Neumann-type boundary condition is the same as that for Dirichlet-type one. A cylindrical mesa is then proposed in this study to determine the boundary condition uniquely. The measurement of the radiation frequency as a function of cylinder radius by experiment directly gives the correct boundary condition and the resonant modes, because the zeros of the Bessel function is different from the zeros of the derivative of the Bessel function. The theoretical proposal was checked by experiments recently and the Neumann-type boundary condition has been convincingly confirmed.

To summarize, the inductively coupled sine-Gordon equations have been investigated theoretically in the present study, and a new state of superconductivity phase dynamics in IJJs of cuprate high-Tc superconductors under voltage bias has been revealed. The theoretical results explain the key features of the experimental observations. It is predicted that the optimal radiation power is stronger than the observed value so far by orders of magnitude. The present study suggests that the IJJs of cuprate high-Tc superconductors can be a practically useful source of THz EM waves.

審 査 の 結 果 の 要 旨

本研究は、直流電圧バイアス印加下に於ける銅酸化物高温超電導固有ジョセフソン接合系の超伝導位相ダイナミクスを理論的に調べたものである。接合間に強い誘導相互作用がある場合、πキンク状態と呼ばれる超伝導位相の新しいダイナミク状態を初めて見出し、ジョセフソン接合系の新しい電気力学特性を明らかにした。これらの研究結果は、ジョセフソン効果に基づく強いテラヘルツ電磁波発振に関する新しい知見をもたらした。以上の理由から、本論文は博士論文として十分と判断された。

よって、著者は博士（工学）の学位を受けるに十分な資格を有するものと認める。