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学 位 論 文 題 目	

Study on Inductively Coupled Sine-Gordon Equations as a Model for Intrinsic Josephson Junctions toward Terahertz Electromagnetic Radiation
（テラヘルツ電磁波発振に向けた固有ジョセフソン接合系のモデルとしての誘導結合サイン-ゴルドン方程式の研究）

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論 文 の 要 旨

Generation of electromagnetic (EM) waves is considered as one of the most highly developed scientific and technological fields and their applications are ubiquitous in our daily life. However the EM waves in the terahertz (THz) band, a region lying between radio waves and infrared light with plentiful applications ranging from safety checks, imaging to radar, still lack an efficient and compact generator.

Josephson effects in Josephson junction consisted of a blocking layer sandwiched by two superconducting electrodes provides us a unique method to excite EM waves with high frequencies. In the presence of a biased voltage, the super-current oscillates at a frequency proportional to the voltage according to the ac Josephson relation, and 1mV corresponds to 0.48THz. Collective motions of cooper pairs and EM waves known as Josephson plasma are excited. At the edges of the junction, part of the energy in Josephson plasma radiates into free space. Nevertheless the power radiated from a single junction is in range of picowatts which is too small for practical applications. The intrinsic Josephson junctions (IJJs) formed by single crystal of cuprate high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) have the following advantages as compared with conventional low-temperature Josephson junctions. First, the superconducting energy gap is large (~60meV) which in principle can cover the whole THz range. Second, the junctions are

homogeneous in atomic scale which favors coherent THz radiation. These merits make IJJs fantastic candidates as sources of powerful EM radiation in THz band.

An experimental breakthrough was achieved in 2007. By applying a c-axis bias voltage, experimentalists successfully excited coherent THz radiation from a rectangular mesa mounted on the top of a substrate of a single crystal of BSCCO. The radiation frequency and bias voltage obey the ac Josephson relation, and strong radiation happens at cavity frequencies determined by the lateral size of the mesa. The significant experimental discovery showed the potential to pave a practical way for strong radiation sources of THz band in a compact and solid device based on superconductivity. The experimental breakthrough inspired intensive discussion from both experimental and theoretical sides. Lin and Hu investigated the phase dynamics of IJJs under bias current in terms of sine-Gordon equations with strong inductive coupling. They proposed a novel π phase kink state, which explains successfully the experimental results mentioned above. In the π kink state, $\pm\pi$ kinks in gauge-invariant phase difference in IJJs are developed in in-plane directions and arrange themselves alternatingly along the c direction. The uniform bias current and cavity modes are coupled by the π phase kink, which allows a large super-current flow into the system at the cavity resonances, and a part of dc energy is converted to EM radiation from the mesa edge.

From application perspective, the radiation power ~10 nW in the present experimental design is still too weak to be practically useful. There are several possible reasons: first, the system may not be synchronized to a uniform state efficiently; secondly, the radiation power may be limited by the small radiation area of the system. In this thesis, the candidate mainly discusses three aspects of THz radiation from IJJs based on inductively coupled sine-Gordon equation for the superconducting phase dynamics.

First, the candidate tries to reveal possible ways to synchronize efficiently IJJs to the π phase states. The candidate has studied phase dynamics starting from random and typical ordered initial phase configurations by numerical simulations. It is found that for random initial phase configurations the system can be driven into the π kink state, and that the average time spent before entering the π phase kink states is shorter when the standard deviation of random distribution is larger, which corresponds to higher temperature of system.

Secondly, the candidate derives an accurate solution for the coupled sine-Gordon equations especially valid for high cavity modes and weak or moderate inductive couplings, where the π kink state is unstable. This new solution is characterized by a structure in phase difference varying in lateral directions around $\pm\pi/2$ in form of cavity mode and an alternating configuration along the c-direction similar to the π phase kink state, and can pump large dc energy into IJJs. Compared with the π kink state, the static term in phase difference of this new solution does not saturate to π and 0 at the sample edges. Increasing the inductive coupling, this new solution evolves smoothly into the π phase kink state.

Thirdly, in order to enhance the total radiation power from IJJs, the candidate investigates a long cylindrical sample embedded in a dielectric material. The candidate finds that, tuning the dielectric constant, the radiation power achieves a maximum when it equals the dissipation caused by the Josephson plasma. From this behavior, the candidates derived the optimal dielectric constant of the wrapping material in terms of the properties of a BSCCO single crystal. The maximal radiation power is found proportional to the product of the critical superconducting current squared and the typical normal resistance, which offers a guideline for choosing superconductors as a source of strong radiation.

To summarize, in this thesis several interesting aspects of THz radiation from IJJs have been investigated by solving the coupled sine-Gordon equations numerically and analytically. The candidate finds that the IJJs can be driven into the π kink state efficiently from a random initial phase configurations. The candidate finds a new solution valid for high cavity modes and weak or moderate inductive couplings, which can pump large energy at resonances. The candidate also proposes a long BSCCO cylinder embedded in a dielectric material with large radiation area and find the optimal radiation power.

審　査　の　要　旨

〔批評〕

本研究は、銅酸化物高温超伝導体の固有ジョセフソン接合における超伝導量子位相が満たす連立サイン・ゴルドン方程式を理論的に調べたものである。特に、今までに知られていた超伝導位相のパイキンク状態の実現における熱揺らぎの有効性の確認、超伝導層間誘導的結合が弱い場合の新しい動的状態の発見、大きな輻射面積をもつ銅酸化物高温超伝導体の共振器形成の新しい方法の提案等の新しい知見を得た。これらの結果は、今後銅酸化物固有ジョセフソン接合による強いテラヘルツ電磁波発振の実現に向けた実験探索の指針になりえるものである。

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。

〔最終試験結果〕

平成27年6月24日、数理物質科学研究科学位論文審査委員会において審査委員の全員出席のもと、著者に論文について説明を求め、関連事項につき質疑応答を行った。その結果、審査委員全員によって、合格と判定された。

〔結論〕

上記の論文審査ならびに最終試験の結果に基づき、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。