Possible Ways to Synchronize Phase Dynamics in Intrinsic Josephson Junctions for Terahertz Radiation

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Coherent terahertz radiations based on intrinsic Josephson junctions from a Bi2Sr2CaCu2O8+δ mesa under a bias voltage were observed in 2007. Later on a novel π phase kink state was proposed which can explain the key experimental results. However, how to drive the system into the π phase kink state efficiently still remains an open problem. In this work we propose several ways to synchronize the system to the π phase kink state. We start from random and typical regular initial phase configurations. It is found that starting from some initial phase configurations the system can be driven efficiently into the π phase kink state. The time spent before entering the π phase kink states for these initial phase configurations is shorter when the initial phase configuration is further away from the uniform phase configuration.

*Keywords*: Intrinsic Josephson junctions; π kink state; Synchronization.

# Introduction

Electromagnetic (EM) waves in terahertz (THz) band have many useful applications such as radar, imaging, safety check and so on. However, they are not easy to be generated by conventional electronic and optical devices. The Josephson effect in Josephson junctions made of an insulating layer sandwiched by two superconducting electrodes provides a unique way to generate high-frequency EM waves.1, 2 In the presence of a bias voltage, the phase oscillates at a frequency proportional to the voltage according to the ac Josephson relation. Collective excitations of Cooper pairs and EM waves known as Josephson plasma are excited. At the edges of the junction, a part of energy of the 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) in high-Tc superconductor Bi2Sr2CaCu2O8+δ (BSCCO) single crystal is a nice candidate for the realization of powerful THz radiation. 3 Compared with conventional low-temperature junctions the IJJs have the following advantages. First, the superconducting energy gap is large (60meV) which in principle can cover the whole THz range. Secondly, the junctions are homogeneous in atomic scale which makes coherent THz radiation possible.

The coherent terahertz radiation with radiation power of order of 1µW was achieved experimentally from IJJs based on a BSCCO mesa without external magnetic field and under a dc bias current in 2007. 4 The radiation frequency and bias voltage obey the ac Josephson relation and the strong radiation happens at cavity frequencies determined by the lateral size of the mesa used in the experiment. THz radiation from IJJs was also observed in other experiments with high power and different geometry.5-9 It was also demonstrated that radiation frequencies can be tuned to certain degree.10 These experiments challenged our theoretical understanding of the coherent radiation. For instance, it was not known how synchronization is achieved in IJJs with such a large number of junctions (∼1000). It was not clear how the power is pumped into the Josephson plasma. In 2008 a novel π phase kink state was proposed, which can explain the key experimental results mentioned above.11-16 This state is characterized by ±π phase kinks in the lateral directions of the mesa, which align themselves alternatingly along the c-axis. With the help of the π phase kink, a great amount of energy can be pumped into cavity modes at resonance frequencies from the dc current and a strong coherent radiation occurs.1

The π phase kink state offers us a possible way for the realization of the powerful coherent THz radiation from IJJs. How to drive the system into the π phase kink state efficiently is an interesting issue. In this work, we propose to synchronize the system to the π phase kink state by preparing initial phases, which can be done by applying non-uniform voltages or making using of thermal fluctuations. Several initial phase configurations are studied, such as random and some typical regular distributions. It is found that the system can be driven into the π phase kink states in several cases. The time before entering the π phase kink states is shorter when the initial phase configuration is further away from uniform phase configuration.

# Model

We consider a stack of IJJs with lateral sizes Lx=80µm and assume that the superconducting phase is uniform along y-axis. The dynamics of the gauge-invariant phase difference in the *l*-th junction γl can be described appropriately by the inductively coupled sine-Gordon equations, which are given in the dimensionless form as1



, (1)

where the lateral length and time are scaled by the penetration depth λc and the inverse of intrinsic plasma frequency  respectively; the external current is in units of Josephson critical current Jc= cϕ0/8π2λ2cs (s standing for the period of BSCCO lattice in the c direction); ζ ≡ (λab/s)2 is the inductive coupling with λab the penetration depth of lateral plane;  is the normalized c-axis conductivity of BSCCO sample; △(2)γl= γl+1+γl−1−2γl is the second-order difference operator along the c-axis.

To simulate the phase dynamics of the system, we integrate Eq.(1) with the leapfrog algorithm under a bias voltage corresponding to one of the cavity modes determined by Lx.11 As the boundary condition we adopt the one for perfect magnetic conductor, namely ∂xγ(x = 0,Lx) = 0 because the impedance is huge at the edges of junctions Z ∼ λ/hz with hz the thickness of BSCCO mesa and λ the wave length of electromagnetic fields.17 To reveal the physics under concern, we adopt periodic boundary condition along c-axis. The parameters are chosen as β = 0.02 and ζ = 4×104, which are typical values for BSCCO single crystal. The bias voltage is set as 1.2mV corresponding to the (1, 0) mode.

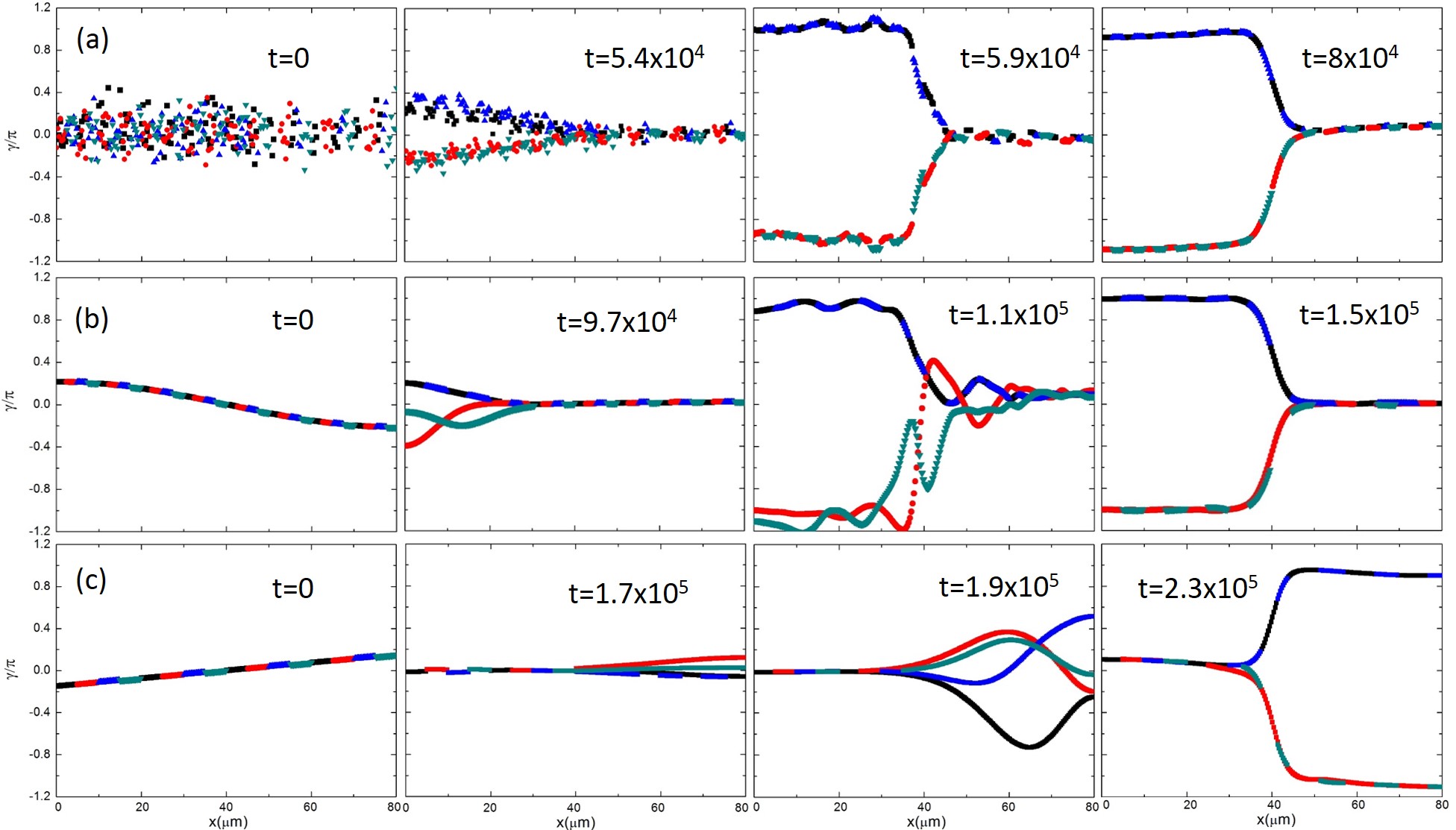


Fig. 1.   Snapshots of simulated phase dynamics starting from initial phase configurations: (a) random distribution with σ = 0.5; (b) γl(x, t = 0) = 0.3πcos(πx/L) and (c) γl (x, t = 0) = 0.28π(x/L − 1/2). Starting from these three types of phase configurations the system can be driven into the π phase kink state. The blue and the black (the green and the red) colors represent the odd (even) junction indices in c direction. The temporal linear part in phase determined by the bias voltage has been removed for clarity. The bias voltage is set as 1.2mV corresponding to the (1, 0) mode. The time is in units of 1/ωp.

# Simulation results

There are two typical states in the system. One is the McCumber state where the phase is uniform in space and is increasing linearly with time, for which no resonance phenomena can be expected. The other one is the alternating π phase kink state mentioned above which can pump large energy into the cavity mode at resonances.

We start from a random initial phase configuration given as



(2)

with σ the standard derivation. The system can be driven into the π phase kink state as shown in Fig. 1(a). We investigate 600 independent samples and then count the time that the system spends before entering the π phase kink state. The criterion for formation of the π phase kink state is that there should be (2n + 1)π phase kinks in the phase at the nodes of electric field with n an integer. For the initial configurations with which the system falls into the McCumber state, the consuming time is taken as infinitely long. The average time that the system spends before entering π phase kink states is displayed in Fig. 2 when the standard deviation σ is varied. As we can see from Fig. 2, the average time is shorter when σ is larger, which suggests thermal fluctuations can help synchronize the system.

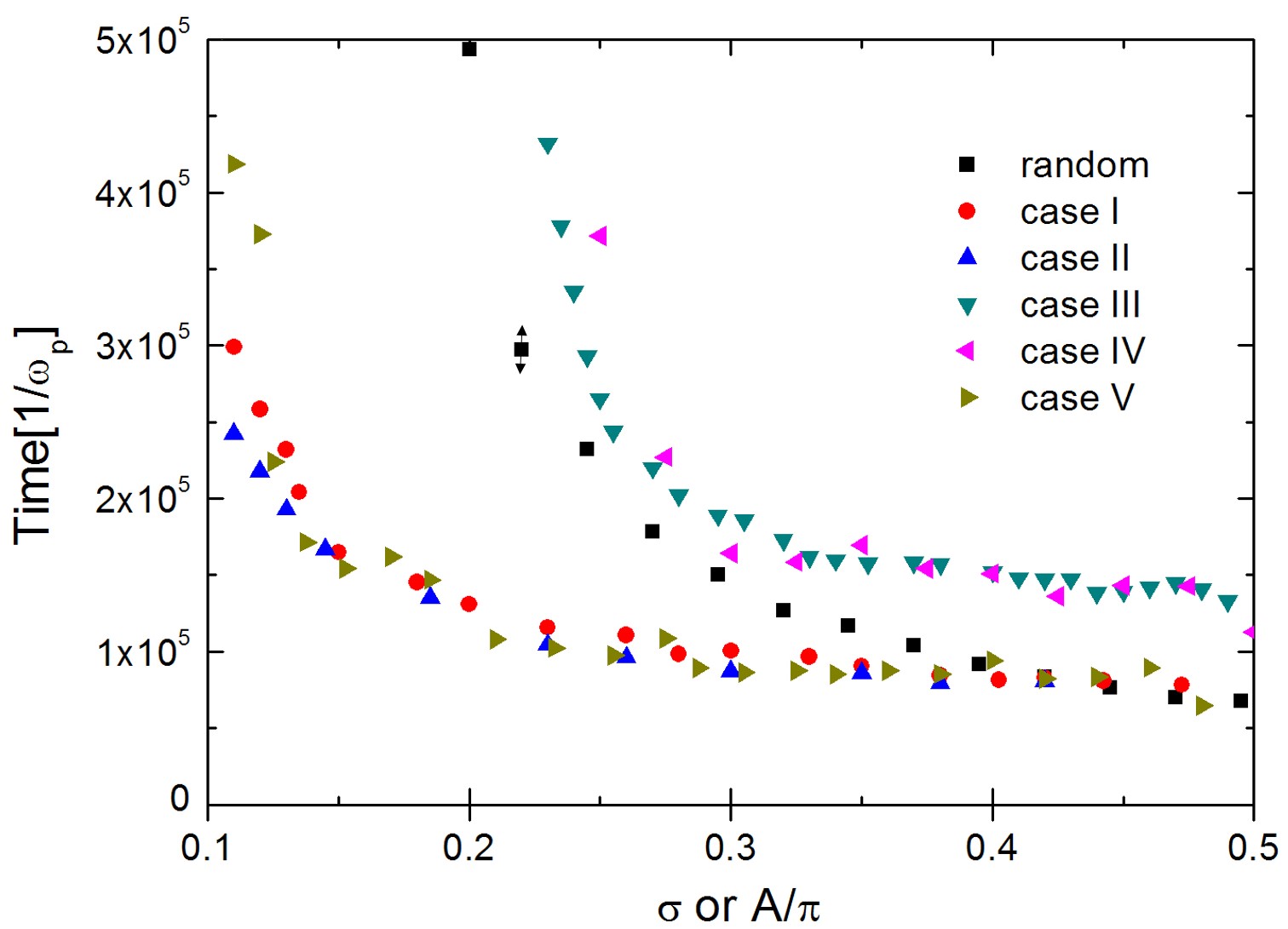


Fig. 2.   (color online) Standard deviation σ or amplitude of ordered initial phase configuration A dependence of time that the system spends before entering the π phase kink state for various initial configurations. For random initial distribution the time is evaluated by averaging on 600 samples and the error bar is about 5%. For distributions of ordered initial phase configuration please refer to the text.

In order to make comparison, we also study several typical ordered initial phase configurations such as case I: γl(x, t = 0) = Acos(πx/L); case II: γl(x, t = 0) =Acos(πx/L + 0.1π); case III: γl(x, t = 0) = A(x/L − 1/2); case IV: γl(x, t = 0) =A(x/L − 0.45) and case V: γl(x, t = 0) = Asin(2πx/L). It is found that in all these cases, the system can be driven into the π phase kink state for large enough amplitudes. The minimal amplitude for case I is 0.11π, for case II is 0.1π, for case III is 0.23π, for case IV is 0.21π and for case V is 0.11π. Several snapshots of phase for A = 0.3π of case I and for A = 0.28π of case III are shown in Fig. 1(b) and (c) respectively. The time spent before entering the π phase kink state is shown in Fig.2 when the amplitude A is varied.

Some other ordered initial phase states are also studied such as case VI: γl(x, t =0) =Asin(πx/L) and case VII: γl(x, t = 0) =Acos(2πx/L). We find that in these two cases, the system cannot be driven into the π phase kink states. This is because of that the distributions of phases in cases VI and VII are similar to the (2, 0) mode, and thus the energy cannot be pumped into the system at the (1, 0) mode frequency given by the bias voltage.

# Conclusion

In order to reveal the way to synchronize efficiently the intrinsic Josephson junctions to the π phase states, we have studied phase dynamics starting from random and several 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 phase kink states. The average time spent before entering the π phase kink states is shorter when the standard deviation of random distribution is larger corresponding to higher temperature. The system can be driven into the π phase kink state staring from several typical initial phase configurations, which can be done by applying a non-uniform bias voltage.

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