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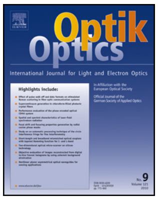

Original research article

Synchronized Josephson junctions and terahertz waves

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ABSTRACT

Chaos synchronization between Josephson junctions coupled bidirectionally with coupling time-delay is investigated. The results are compared with the case of junctions coupled in a unidirectional and mixed (both unidirectional and bidirectional couplings) configurations. We establish that bidirectional coupling between the junctions deteriorates synchronization quality significantly, and as such should be avoided in cases when a large number of the Josephson junctions are to be synchronized. Synchronized Josephson junctions can be a source of Terahertz radiation with enough power, which is promising for practical applications in numerous scientific areas.

1. Introduction

Terahertz (THz) radiation (from 0.3 to 3 THz) is placed between microwaves and infrared light waves. Due to the fact that THz waves have a wide range of possible uses, including security scanning, remote sensing chemical signatures of explosives, non-invasive applications in medicine, ecology, secure communication [1–4], technology for generating and manipulating THz radiation is the subject of intense research, see e.g. [1–3] and references there-in. Although currently there are a lot of viable sources of THz radiation, such as the gyrotron, the far infrared laser, the free electron laser, quantum cascade laser, etc. [1–3], as a rule these sources of THz waves require a lot of space, not portable, and importantly need costly deep cooling procedure. These factors stimulate the need for developing compact, cheap, and portable THz sources. In addition, for many remote sensing and imaging applications high power THz sources are desirable [5].

Nowadays it is well established that Josephson junction is also a source of radiation with frequencies up to THz region [6–13]. Unfortunately the radiation from a single Josephson junction is very weak, usually from 1 pW to nW [12,14]. Synchronization of the arrays of Josephson junctions is one of the ways to increase the radiation power from such sources [6–13]. Upon achieving synchronization the coherent radiation power will be proportional to the number of Josephson junctions squared. Fortunately recently it was established that certain highly anisotropic high temperature cuprate superconductors [15], such as BSCCO naturally contain a stack of thousands strongly electromagnetically coupled intrinsic Josephson junctions [6–13]. The intrinsic Josephson junctions in high-T_c BSCCO crystal is a good candidate for the realization of powerful THz radiation. Compared with Josephson junctions in low-T_c materials high-T_c crystals have some advantages for the following reasons: first, the superconducting energy gap is large (the energy gap of BSCCO ranges from 10 to 60 meV, which corresponds to a gap frequency of 5–30 THz) which can cover the wide range; secondly, the junctions are homogeneous in atomic scale which makes coherent THz radiation possible [6].

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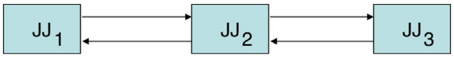

Fig. 1. Schematic sketch of three bidirectionally coupled Josephson junctions. JJ stands for Josephson junction.

In [16] we have studied chaos synchronization between unidirectionally coupled Josephson junctions. We have established that it is possible to synchronize several tens of such junctions in such a configuration. In [17] we have investigated the stack of Josephson junctions governed by a central junction. It has been shown that with this coupling topology it is possible to synchronize several hundreds, or even probably thousands junctions. As it follows from these results, the coupling topology is important for the number of junctions to be synchronized. As mentioned above there are thousands of naturally intrinsic Josephson junctions in some of high-T_c superconducting crystals. If needed, for technological purposes such high number of junctions can be engineered artificially. From this point of view it is of enormous practical importance to study further the effect of coupling topology on the synchronization quality among the Josephson junctions.

In this paper we study synchronization between bidirectionally coupled Josephson junctions and compare the results with the case of unidirectionally coupled systems. Furthermore we also compare the results with the case of systems coupled in a mixed configuration, e.g. coupling between the first two junctions is unidirectional, while the remaining junctions are coupled bidirectionally. We establish that in terms of synchronization quality unidirectionally coupled systems performs better. These findings are also specially important in the context of Josephson junctions governed by the central junction, where the coupling between the governing central junction and the rest of junctions is unidirectional.

2. Bidirectionally coupled RC-shunted Josephson junctions

Consider the following model of three identical bidirectionally coupled (Fig. 1) RC-shunted Josephson junctions written in the dimensionless form:

$$\frac{d^2\phi_1}{dt^2} + \beta\frac{d\phi_1}{dt} + \sin\phi_1 = i_{dc} + i_0\cos(\Omega t + \theta) - \alpha\left(\frac{d\phi_1}{dt} - \frac{d\phi_2(t-\tau)}{dt}\right) \tag{1}$$

$$\frac{d^2\phi_2}{dt^2} + \beta\frac{d\phi_2}{dt} + \sin\phi_2 = i_{dc} + i_0\cos(\Omega t + \theta) - \alpha\left(\frac{d\phi_2}{dt} - \frac{d\phi_1(t-\tau)}{dt}\right) - \alpha\left(\frac{d\phi_2}{dt} - \frac{d\phi_3(t-\tau)}{dt}\right) \tag{2}$$

$$\frac{d^2\phi_3}{dt^2} + \beta\frac{d\phi_3}{dt} + \sin\phi_3 = i_{dc} + i_0\cos(\Omega t + \theta) - \alpha\left(\frac{d\phi_3}{dt} - \frac{d\phi_2(t-\tau)}{dt}\right) \tag{3}$$

where ϕ_1, ϕ_2, and ϕ_3 are the phase differences of the superconducting order parameter across the junctions 1, 2 and 3, respectively; β is called the damping parameter $(\beta R)^2 = \hbar(2eI_cC)^{-1}$, where I_c, R and C are the junctions' critical current, the junction resistance, and capacitance, respectively; β is related to McCumber parameter β_c by $\beta^2\beta_c = 1$; $\hbar$ is Planck's constant divided by 2π; e is the electronic charge; i_{dc} is the driving the junctions direct current; $i_0\cos(\Omega t + \theta)$ is the driving ac (or rf) current with amplitudes i_0, frequencies Ω and phases θ; τ is the coupling delay times between the junctions 1 and 2 and 2 and 3; coupling between the junctions 1 and 2 and 2 and 3 is due to the currents flowing through the coupling resistors R_s between the junctions 1 and 2 and between the junctions 2 and 3; $\alpha = R\beta R_s^{-1}$ are the coupling strengths between junctions 1 and 2 and junctions 2 and 3. We note that in Eqs. (1)–(3) direct current and ac current amplitudes are normalized with respect to the critical currents for the relative Josephson junctions; ac current frequencies Ω are normalized with respect to the Josephson junction plasma frequency $\omega^2 = 2eI_c(\hbar C)^{-1}$ and dimensionless time is normalized to the inverse plasma frequency.

Treating Ωt term as a new dynamical variable Eq. (1) (and consequently Eqs. (2) and (3)) can be rewritten as a system of third-order ordinary differential equations:

$$\frac{d\phi_1}{dt} = \psi_1 \tag{4}$$

$$\frac{d\psi_1}{dt} = -\beta\psi_1 - \sin\phi_1 + i_{dc} + i_0\cos\varphi_1 - \alpha(\psi_1 - \psi_2(t-\tau)) \tag{5}$$

$$\frac{d\varphi_1}{dt} = \Omega \tag{6}$$

$$\frac{d\phi_2}{dt} = \psi_2 \tag{7}$$

$$\frac{d\psi_2}{dt} = -\beta\psi_2 - \sin\phi_2 + i_{dc} + i_0\cos\varphi_2 - \alpha(\psi_2 - \psi_1(t-\tau)) - \alpha(\psi_2 - \psi_3(t-\tau)) \tag{8}$$

$$\frac{d\varphi_2}{dt} = \Omega \tag{9}$$

$$\frac{d\phi_3}{dt} = \psi_3 \tag{10}$$