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Coherence of Josephson soliton oscillators in the millimeter-wave range

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We report on the observation of phase-locking and radiation enhancement from two dc series-biased Josephson fluxon oscillators ac-coupled by a thin film-integrated capacitor. The radiation is detected by a small area Josephson junction displaying, under the effect of the radiation, critical current suppression and Shapiro steps at a voltage of 220 μV. The phenomena that we observe are the higher frequency counterpart of the superradiant effects measured by means of X-band room temperature receivers detecting the radiation emitted by series arrays of long Josephson junctions.

The possibility of fabricating coherent arrays of one-dimensional long Josephson junctions (LJJ) is a research subject which has recently attracted attention both from the theoretical [1,2] and from the experimental point of view [3,4]. Coherent arrays could increase the power of the radiation emitted by LJJs and their practical potentiality as millimeter or submillimeter wave oscillators in superconducting electronics. However, due to the complexity of the internal dynamics of LJJs, regulated by perturbed sine-Gordon equations [5], conjecturing phase-locking criteria is a very difficult task: the problem falls in the general class of the phase-locking of spatially distributed nonlinear oscillators, a theme recurring even in other fields of physics [6].

Phase-locking of LJJs was first investigated by Finnegan and Wahlsten [7] who reported that, under particular current biasing conditions, a superradiant state of two LJJs could be observed. In a superradiant state the power emitted by an array of junctions must increase as the square of the number of the junctions. This phenomenon has also been measured recently on larger arrays of junctions [3,4] emitting radiation in the X-band region of the electromagnetic spectrum. In both the cases of ref. [3] and ref. [7] phase-locking was observed only for tiny frequency (or voltage) intervals, likely because the oscillators were not provided by phase-locking devices or circuits. Mutual phase-locking of LJJs via a linear resonator has been recently studied both theoretically and experimentally with interesting results having been obtained [1,4]. A scheme of capacitive coupling which does not imply the use of a resonator has been analyzed theoretically [2]: the analysis has shown that radiation transmission is sufficient to generate phase-locking of the oscillators. The same coupling scheme had already been employed in experiments to couple radiation from a LJJ oscillator to a point Josephson junction [8]. In this paper we show experimental evidence that the capacitive coupling can provide both phase-locking of oscillators (giving rise to a substantial increase of the power of the radiation) and pumping devices.

Before giving some details of our fabrication process we recall that by long Josephson junction we

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mean a rectangular Josephson junction having at least one physical dimension larger than the Josephson penetration depth $\lambda_j = (\Phi_0/2\pi J_c\mu_0 d)^{1/2}$ [9]. Here J_c is the critical current density of the junctions, $\Phi_0 = 2.07\times10^{-15}$ Wb is the quantum of magnetic flux or fluxon, $d = \lambda_{Nb} + \lambda_{PbAuIn} + t$ is the sum of the London penetration depths of the superconducting electrodes forming the junctions and the thickness (t) of the oxide barrier. In our experiments, in order to deal, as much as possible, with one-dimensional fluxon motion, we always try to keep only one dimension of the junction larger than λ_j. We recall that the reflections of the fluxons at the ends of the LJJs is the periodic phenomenon that gives rise to radiation emission at an "asymptotic" frequency of $\bar{c}/2L$, where $\bar{c}$ is the electromagnetic wave propagation velocity in the oxide barrier and L is the physical length of the oscillators [8].

A scheme of our physical system is shown in fig. 1a. The two narrow and long shaded areas to the right and to the left of the center one (the detector junction) represent the SiO windows giving rise to the two LJJs. The fabrication of our samples follows the procedures described in ref. [8]: the Josephson junctions are Nb–SiO–PbAuIn tunnel sandwiches whose oxide barrier is formed by a very standard plasma-oxidation procedure [10]. As we can see in fig. 1a the three junctions have in common the niobium base electrode while their top electrodes are separated. Once the counter electrode of the junctions has been evaporated and patterned, two more layers complete the samples. The last two layers consist of an SiO isolating layer and of a PbAuIn top plane. The choice of the thickness of the latter SiO layer, of the critical current density and the dimensions of the junctions have been made considering the theoretical analysis reported in ref. [2] as starting point. A detailed discussion of our progress concerning this interesting impedance-matching problem which is a crucial point for the working-principle of our coupled oscillators, shall be dealt with in a future work. In this paper we report data on a sample having a Josephson current density of 820 A/cm^2 and having therefore a $\lambda_j \approx 13$ μm (assuming $d \approx 200$ nm); the length L of the two LJJs was 60 μm. The data relative to this sample show very good dc and ac evidence of phase-locking between the oscillators.

The two oscillators of fig. 1a can be dc-biased independently as well as in series while the central window junction, dc-isolated from the LJJs, can be also independently biased. A typical current–voltage characteristic of the two oscillators is shown in fig. 1b: in this figure indeed we show a current–voltage characteristic of the series connection of the two oscillators showing the zero-field steps (ZFS) of the series connection. These steps are the dc manifestation of fluxon oscillation inside the long junctions: each single LJJ of fig. 1a exhibits only one singularity having an asymptotic voltage of 440 μV which is the voltage corresponding to the second zero-field step (the first Fiske step appeared at about 110 μV). The minimal frequency of emission related to a ZFS voltage of 440 μV when radiation is detected only from

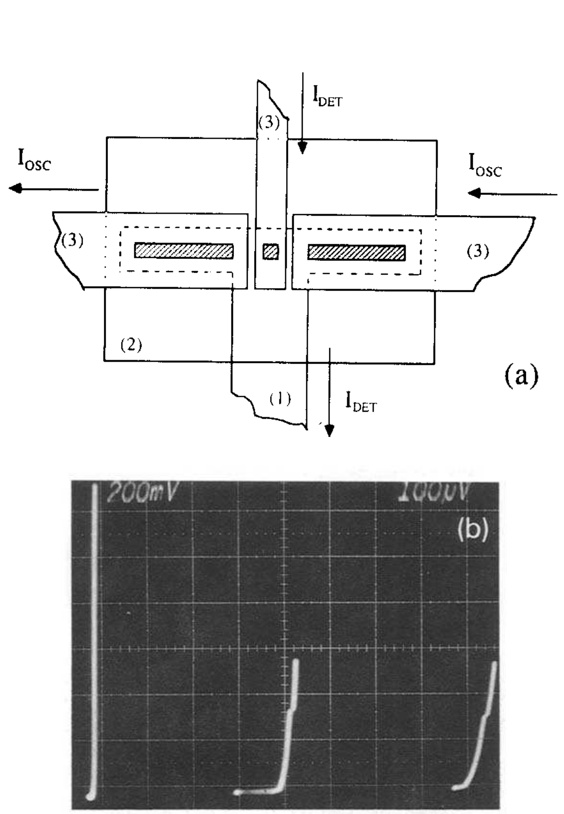

Fig. 1. (a) Sketch (not to scale) of our oscillators-detector system. I_{osc} represents the dc-bias current driving the oscillators and I_{DET} the current feeding the detector. (1) The first (Nb), (2) the second (SiO) and (3) the third layer (PbAuIn alloy) in our fabrication process. (b) Current–voltage characteristic of the series connection of the two oscillators showing the Josephson current and the two zero-field steps; current scale is 200 μA/div.

one end of the junction is 53 GHz (assuming that soliton bunching is taking place [11]). We observed Shapiro steps of the detector junction at a voltage of 220 μV, corresponding to the first harmonic of this fundamental frequency.

Fig. 2 shows the current–voltage characteristics of the two oscillators when they are biased separately; it is evident that the shape of the two steps is different for the two oscillators, indicating the existence of slightly different dissipation mechanisms in the junctions, most likely due to tunnel barrier inhomogeneities. However, we can see that the ZFS shown in fig. 2a has roughly the same form as the two shown in fig. 1. We note in particular the discontinuity in the profile that appears 200 μA below the top of the ZFS of fig. 1b and of fig. 2a. This result indicates that one LJJ oscillator is driving the other to have the same frequency of oscillation and therefore the zero-field steps of the series connection appear to have the same profile. From this qualitative dc evidence of phase-locking we would think that phase-locking is achieved all over the ZFS range of allowed dc-bias current.

Beside the dc evidence, a much more clear indication that mutual phase-locking is taking place is obtained looking at the current–voltage characteristic of the detector junction. We have measured that, biasing the two oscillators independently on their ZFSs, the maximum suppression of the Josephson current of the detector that can be observed is about 13%. The current–voltage characteristic of the detector junction is shown in fig. 3a, where we see that the maximum critical current, when the oscillators are off, is 160 μA. When the dc-series connection of the oscillators instead is biased even just at the bottom of the ZFS displayed around 800 μV in fig. 1b, the result on the critical current suppression of the detector is the one shown in fig. 3b: now the Josephson current is depressed to about 87% (note that

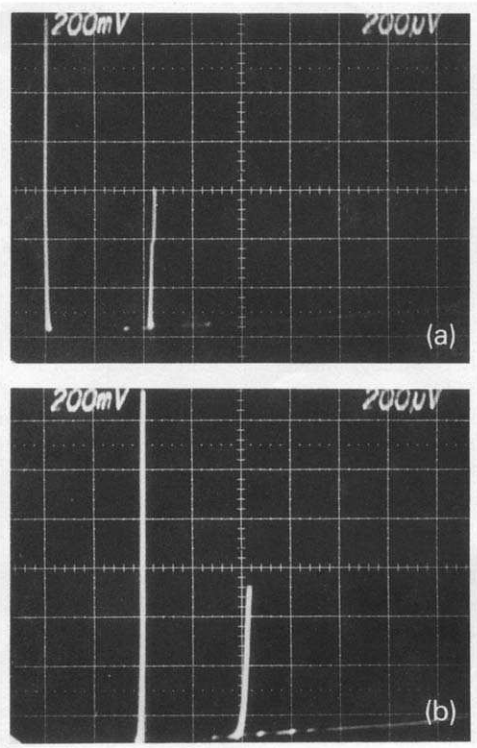

Fig. 2. (a), (b) The zero-field steps of the long junctions biased separately: note that the shape of the step in (a) is very similar to the two shown in fig. 1b; current scale is 200 μA/div for both (a) and (b).

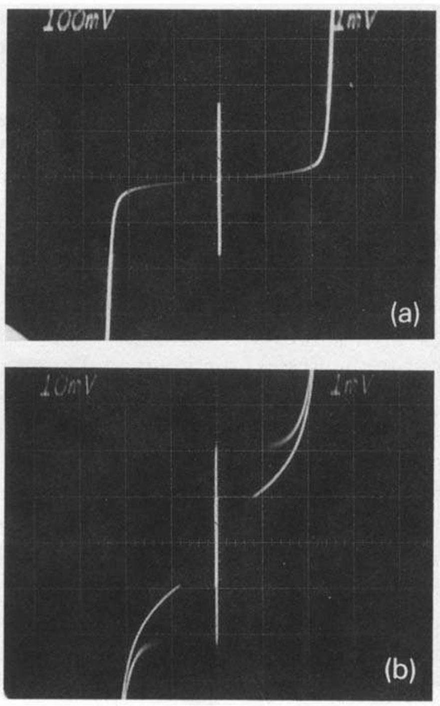

Fig. 3. (a) The Josephson current of the detector junction with the oscillators off. (b) Depression of the current shown in (a) with the oscillators dc-biased on the 880 μV step shown in fig. 1b. Current scales: (a) 100 μA/div, (b) 10 μA/div.

there exists one order of magnitude difference between the current scales of figs. 3a and 3b). By a fine tuning of the dc-bias point on the ZFS appearing at the asymptotic voltage of 880 μV in fig. 1b we could even see the Josephson current going through a minimum under the application of the rf power.

We recall that the theory [12] for the rf-driven (point) Josephson junction predicts that the amplitude of the Josephson current is regulated by the zeroth order Bessel function and the argument of the function is proportional to the applied rf voltage. Now, if the junctions are phase-locked in a superradiant state the emitted power increases proportionally to the square of the number of junctions and the rf voltage must increase by a factor two. In our case we observe that the height of the Josephson current of the detector when the LJJs are biased independently on the first ZFS is 87% of the Josephson current with no rf power: this means that the argument of the corresponding Bessel function is about 0.7. When biasing the series of the LJJs on the second ZFS, an increase of the power by a factor four (and the corresponding increase of the Bessel function argument to 1.4) should drive the Josephson current to 56% of its value, i.e. to about 90 μA, which is well above the value that we observe in fig. 3b. Thus, we find that there exists even more power coupled with respect to what is expected in terms of the superradiant model.

Our discussion in terms of Bessel function behavior of the Josephson current has to be considered as a first approach to a quantitative analysis of the possible superradiant state. There exist numberous limitations to the Bessel function modulations in rf-driven Josephson junctions [12]; moreover, we recall that we are surely not driving the detector junction with a sinusoidal signal. A complete modeling of our system (perhaps through numerical simulations) is the way to get more quantitative predictions concerning the rf response of the detector junction. It would be surely interesting to understand why the power levels that we measure from the series connection of the LJJs are larger than what is expected in terms of Bessel function behavior and the superradiant model.

We have shown that it is possible to phase-lock fluxon oscillators at frequencies that can be interesting for pumping superconducting integrated devices such as SIS mixers and Josephson voltage standards. Moreover, we have reported evidence that phase-locking the oscillators does not prevent the enhanced radiation power from getting pumped devices. This is an interesting result whose implications shall be further investigated especially considering that we have tested our coupling scheme over the frequency interval 60–100 GHz without finding substantial changes in the coupling performances.

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