

Chapter 4. Superconducting and Quantum-Effect Devices

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4.1 Nonlinear Dynamics of Discrete Josephson Arrays

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Project Staff

Dr. Herre S.J. van der Zant, Professor Terry P. Orlando, S. Watanabe, S. Strogatz

We have studied the dynamics of circular one-dimensional arrays of underdamped Josephson junctions connected in parallel. In these Josephson rings, a single vortex can be trapped and studied experimentally without complications caused by reflections off boundaries. We find that a propagating vortex can become phase-locked to linear waves excited in its wake. In the I-V curve, resonant steps are observed indicative of this phase-locking. Numerical simulations indicate that, at least in principle, an infinite number of these steps is possible. Resonant steps also occur in the I-V curves for higher voltages in the return path of the subgap region. These resonant steps have a completely different origin and occur at voltages where the periodic whirling solution undergoes an instability parametrically amplified by the linear modes in the system. Only $N/2$ steps are possible with N the number of junctions in the ring. Despite the presence of linear modes, our numerical studies show that a single propagating vortex can, for a certain range of parameters, be viewed as a particle with a long mean free path. This almost free vortex prop-

agation makes discrete Josephson rings ideal systems for further quantum vortex experiments.

4.2 Resonance Splitting in Inductively Coupled Arrays

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Amy E. Duwel, Enrique Trías, Professor Terry P. Orlando, Dr. Herre S.J. van der Zant, S. Watanabe, S. Strogatz

Coupled arrays of one- and two-dimensional Josephson junctions have received renewed attention as model systems for high-temperature superconducting thin films of BSCCO and TBCCO, showing coupling of the discrete layers. These arrays are also of interest since phase locking between the coupled rows decreases the linewidth of the radiation emitted by oscillators made of these arrays.

We have observed that, in long inductively coupled arrays of niobium Josephson junctions, two Eck steps appear in the current-voltage (I-V) characteristic. These steps correspond to arrays of vortices traveling through the system. The wave is composed of nearly a single harmonic with a well-defined amplitude and dispersion relation. We have found that the lower step corresponds to an anti-

symmetric state where the voltages are oscillating out of phase between the two rows. However, the upper step corresponds to a symmetric state, where the oscillating voltages are in-phase. We have found an analytical ansatz for the voltage states which is close to numerical observations. We can analytically predict the DC voltages of these resonant states and numerically predict the amplitude of the AC voltages.

The upper step can have important technological implications. When the system is biased in this state, the AC voltages add, increasing the power output. The two-row device will also have higher output impedance than its continuous, stacked junction counterpart. These qualities make this device desirable for oscillator applications. As in a single row of a discrete array, the frequencies can be tuned with a control current and are stable for a relatively wide range of bias currents. Although the bandwidth is approximately the same as for the single row, a larger output resistance may increase the linewidth. However, phase locking between the two rows is expected to reduce the linewidth, and such measurements will be helpful.

4.3 Flux Flow and Self Field Effects

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Enrique Trías, Dr. Herre S.J. van der Zant, Professor Terry P. Orlando

Measurements and numerical studies of the self-induced magnetic field effects on flux flow in two-dimensional arrays of niobium Josephson junctions have been performed. It was found that the flux-flow resistance becomes larger as the penetration depth of the array decreases. A phenomenological model, which agrees qualitatively with the experiments and simulations, has been developed to explain the self-field effects on flux flow. The main conclusion is that both the mass of the vortex and the array viscosity decrease due to the smaller spatial extent of the vortex current caused by the self-fields.

Vortices in the flux-flow region are localized and, because of the electrical energy in the junctions,

can be treated as massive particles. The applied field specifies the density of vortices present in the array. With this density, the driving force, and the viscosity, we model the dependence of the flux-flow resistance in terms of the array parameters, λ_{\perp} and β_c and applied magnetic field, f . A linear dependence of the flux-flow resistance R_{ff} versus f is found.

It has also been shown that R_{ff} is dependent on both λ_{\perp} and β_c . The dependence on β_c follows from spin-wave damping while the λ_{\perp} dependence is a result of a reduction of the viscosity caused by the decreasing physical size of traveling vortices as λ_{\perp} decreases. This simple phenomenological model gives a qualitative as well as a semi-quantitative description of the dynamics. The effects can also be seen in numerical simulations that take into account all the mutual inductances between cell pairs.

However, the flux-flow region appears to be richer in its dynamics than the presented model can account for. For small arrays, there is a spatial dependence of the flux-flow region which we have measured and also seen in simulations. Different rows have different flux-flow slopes and the outer rows closest to the edge appear to have almost no flux-flow associated with them. Though these deviations do not diminish the useful and intuitive results from the phenomenological model, they do point to further research on flux flow.

4.4 Triangular Arrays of Josephson Junctions

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Project Staff

Amy E. Duwel, Professor Terry P. Orlando, S. Yukon¹

Superconducting arrays of Josephson junctions are important devices for coherent sources of low-power radiation in millimeter and sub-millimeter regime. One- and two-dimensional arrays of Josephson junctions are of particular importance because the phase-locking among the junctions overcomes many of the problems of low impedances and power levels of a single junction.

¹ U.S. Air Force, Rome Laboratory, Rome, New York.

Coherent microwave radiation has been observed in square arrays of Josephson junctions.

In novel geometries based on triangular rather than square arrays, numerical simulations and calculations show a novel and technologically important dynamical state. This state has junctions which generate microwave current and radiation without "going over the top" and producing a DC power loss.

We are developing techniques for designing triangular arrays of Josephson junctions within standard superconducting foundry capabilities. These arrays are predicted to generate AC current without a DC component, and we will explore the feasibility of making microwave measurements on these and other types of Josephson arrays.

4.5 One-dimensional Parallel Josephson-junction Arrays as a Tool For Diagnostics

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Project Staff

Dr. Herre S.J. van der Zant, Professor Terry P. Orlando, in collaboration with A. W. Kleinsasser²

We propose and demonstrate the use of under-damped, one-dimensional parallel arrays of Josephson junctions as a tool for circuit diagnostics. By measuring the Fiske modes and the critical current in a magnetic field, we determined the self and nearest-neighbor inductances as well as the capacitances of single junctions. We have used this technique to find the capacitance of Nb-Al₂O_x-Nb junctions for critical current densities of 0.3 - 20 kA/cm². We find that the specific capacitance increases by about a factor of two over this range. This increase has important consequences for the design of single-flux-quantum circuits and SQUIDs. Measurement of the junction capacitance for critical current densities of 100 kA/cm² is possible, but requires submicrometer junctions with dimensions of the order of 0.3 μm.

4.6 Quantum Device Simulations

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Dr. Chagarn B. Whan, Professor Jacob K. White, Professor Terry P. Orlando

We numerically calculated the full capacitance matrices for both one-dimensional (1-D) and two-dimensional (2-D) quantum-dot arrays. We find that it is necessary to use the full capacitance matrix in modeling coupled quantum dots due to weaker screening in these systems in comparison with arrays of normal metal tunnel junctions. The static soliton (a fundamental electronic charge in the entire array) potential distributions in both 1-D and 2-D arrays are well approximated by the unscreened (1/r) coulomb potential, instead of the exponential fall-off expected from the often used nearest-neighbor approximation. In terms of dynamics, we compare the current-voltage (I-V) characteristics of voltage biased 1-D arrays using either the full capacitance matrix or its nearest-neighbor approximation. The I-V curves show clear differences and the differences become more pronounced when larger arrays are considered.

For quantum dot arrays made by electrostatic confinement of two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures, the array forms a co-planar structure with all dots residing in the 2DEG plane. The co-planar capacitors are far less effective than the parallel plates in terms of confining electric field. Therefore, in comparison with tunnel junction arrays, the field lines originating from one of the quantum dots are much less confined and can reach out to dots that are much further apart. A model that considers only the nearest-neighbor capacitive coupling is unlikely to be accurate in this situation. We now give a more quantitative analysis of this problem.

In our model, the quantum dots (small puddles of a 2DEG) are treated as thin circular shaped conducting plates, with diameter $D = 1 \mu\text{m}$. The plates are arranged to form either 1-D or 2-D arrays with lattice constant $a \cong D + d = 1.1 \mu\text{m}$, where $d = 0.1 \mu\text{m}$ is the closest separation between adjacent dots (or the tunnel barrier width). We believe these values are reasonable for arrays in the classical charging regime with weak inter-dot tunneling (i.e.,

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the tunneling resistance, $R_T \gg R_0 = h/e^2$). Once the array geometry is specified, we compute the full capacitance matrix C of the 1-D and 2-D arrays using FASTCAP, an efficient capacitance extraction tool.

We have calculated the potential distribution due to a soliton being located at the center of a 21×1 series array, using both the full capacitance matrix and its nearest neighbor approximation. The nearest neighbor approximation gives an exponentially decaying soliton potential as expected. However, the soliton potential distribution that result from the full capacitance matrix decays much slower. We find that the soliton potential follows the simple $1/r$ law almost exactly over the entire array, except at the origin where the Coulomb potential is singular.

We have also computed current-voltage (I-V) characteristics of 1-D quantum dot arrays, which is experimentally more relevant. The I-V curves are calculated with both the full capacitance matrix and the nearest-neighbor approximation. The resulting I-V curves show many differences. The threshold voltages are not exactly the same, and the fine structures are different and become more pronounced when we consider larger arrays. At high voltage, the two curves merge and become nearly linear. Hence, we see that the full capacitance matrix is necessary in the dynamical simulation of these arrays.

4.7 Publications

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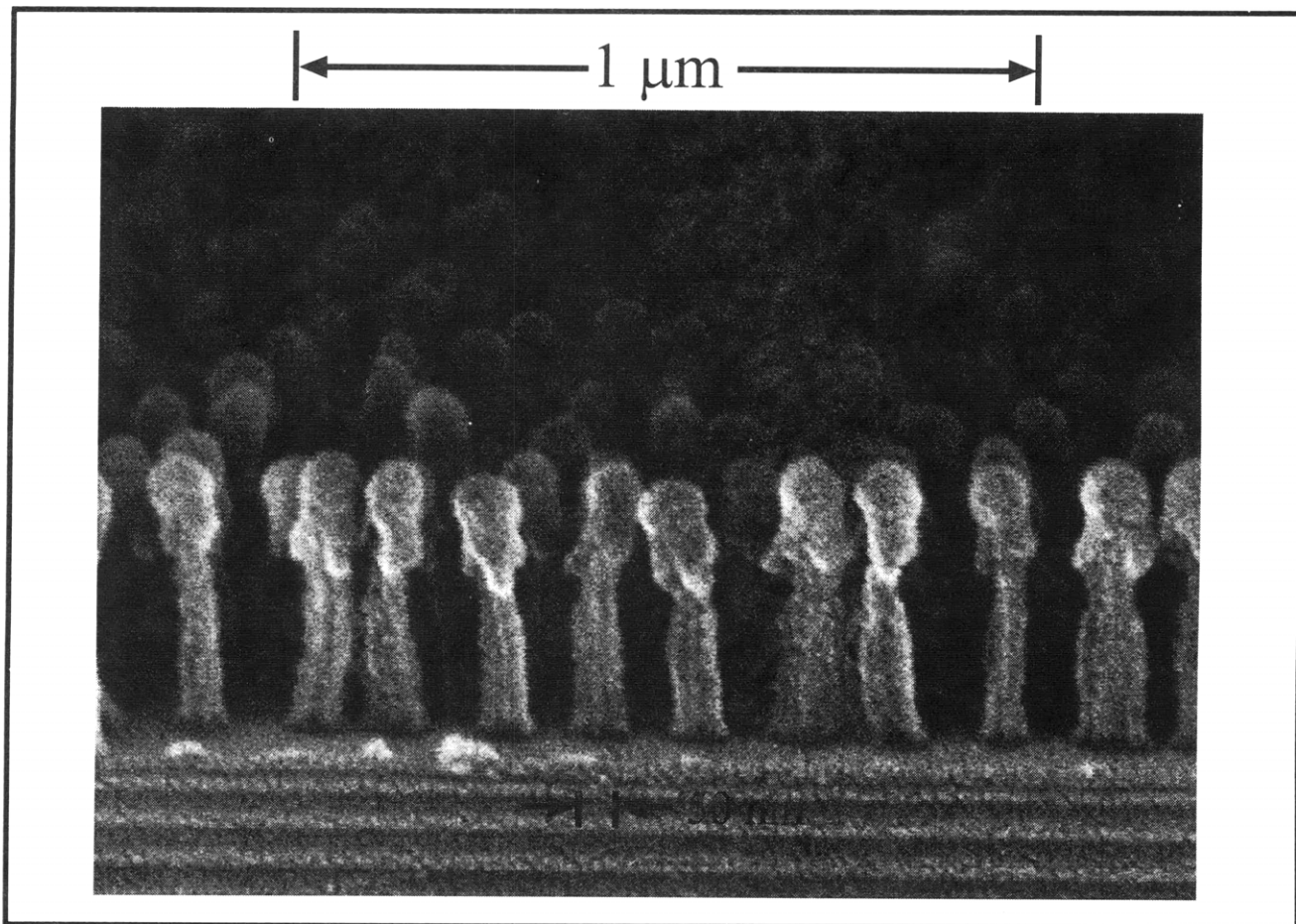
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At the debutante's ball, young nano-women gather in their finery at the edge of the stage to weep because the nano-boys won't dance with them.

An array of 50-nm-wide posts with a periodicity of 100 nm. The posts consist of PMMA on top of an antireflection coating (ARC). The substrate consists of a 250-nm-thick layer of silicon nitride on silicon. The PMMA was exposed using achromatic interferometric lithography. After development of the PMMA, an O₂ reactive ion etch was used to etch through the ARC. SEM viewing caused some melting and charging which resulted in the large gathering of nanopeople. The melting problem was solved by imaging at low voltage.

Timothy A. Savas, a graduate student in RLE's Quantum-Effects Devices Group, submitted this micrograph, which won in the most bizarre category at the Electron Ion Photon Beam Technology and Nanofabrication Conference, Scottsdale, Arizona, in June 1995.