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Antenna coupled planar arrays of Josephson junctions

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Abstract

A novel approach to synchronization of arrays of Josephson junctions (JJA) is proposed. Each Josephson junction is placed in the center of a separate dipole antenna. Antennas at a distance of about a half wavelength from each other form a beam pattern with the main lobe perpendicular to the substrate plane. Two types of JJA were fabricated on $YZrO_2$ and sapphire bicrystal substrates. Self-resonant steps are clearly observed in I–V curves at temperatures 4–60 K. Besides the main resonance at 360 GHz, resonances at voltages corresponding to the second and third harmonics and to subharmonics at 1/2, 3/2, 5/2 of the main resonant frequency are observed. Radiation from such array was observed at bias voltages over 4 mV that corresponds to an oscillation frequency of up to 2 THz. The arrays demonstrated high sensitivity to submm-wavelength radiation in the frequency range 300–550 GHz.

Keywords: Josephson junction arrays; Submm-wave radiation; Oscillation's synchronization

1. Introduction

Arrays of Josephson junctions (JJA) are used in order to improve the sensitivity of detectors, increase the output power and reduce the line width of Josephson oscillators [1]. This is achieved not only because of the increase in impedance of the series array, but mainly because of synchronization of the Josephson oscillations in the junctions [2–4]. The most developed applications of JJA are local oscillators for integrated heterodyne detectors [5–7] and voltage standards [8–10]. The integration of the junctions into arrays is usually done in a semi-lumped fashion; groups of junctions are concentrated in the local (less than quarter-wavelength) region of a long (compared to the wavelength) transmission line. In such layout the equivalent circuit consists of lumped capacitors and inductors, and losses are mainly due to parasitic radiation and mismatch between the individual junctions and the feeding circuit. When the frequency exceeds 100 GHz it becomes problematic to synchronize large amount of junctions in an area larger than about 100 μm^2. All these designs are suffering from increase of losses and reduce of coupling when the frequency is increased.

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One reason is that junctions are integrated into microstrip lines that are relatively lossy and have a low impedance since material and size should be compatible with the junction fabrication process. In Nb technology such lines have characteristic impedance of the order of 1 Ω that is determined by insulator thickness and strip width. An increase in the impedance can be achieved by increasing the insulator thickness and reducing the strip width, but this results in extra radiation losses and reduces the compatibility with current technology for Josephson junction fabrication. A distributed (long) Josephson junction can be viewed as a modification of a parallel array with its disadvantage of high losses in low-impedance microstrip line and mismatch with standard waveguide or quasioptic circuits.

We suggest an alternative approach to the integration and synchronization of Josephson junctions by means of a resonant interaction of oscillations in an array of dipole antennas. In this case the radiation is being converted from stray losses effect to the desired mechanism of interaction. Quasioptical beams and beam guides can be used for low-loss feeding at frequencies over 100 GHz. Such technique brings possibility to directly match the circuit to the incoming radiation in direct detectors or voltage standards, or to feed self-radiation to an external circuit, e.g. Josephson or SIS mixer.

2. Layout

For numerical modeling and experimental studies of the interaction in quasioptical JJA we chose a half-wavelength ($\lambda/2$) dipole array. The design frequency was 350 GHz. We used high quality YBaCuO submicrometer Josephson junctions deposited on sapphire bicrystals. The key issue of the array design is to find the optimal distance between the dipoles. According to [8,9] the array factor is given by

$$\mathrm{AFy} = \frac{\sin(n_x\phi_x/2)}{\sin(\phi_x/2)} = \cos\left(\frac{k_\mathrm{d}\,\Delta d\,\sin\theta\sin\varphi}{2}\right) \qquad (1)$$

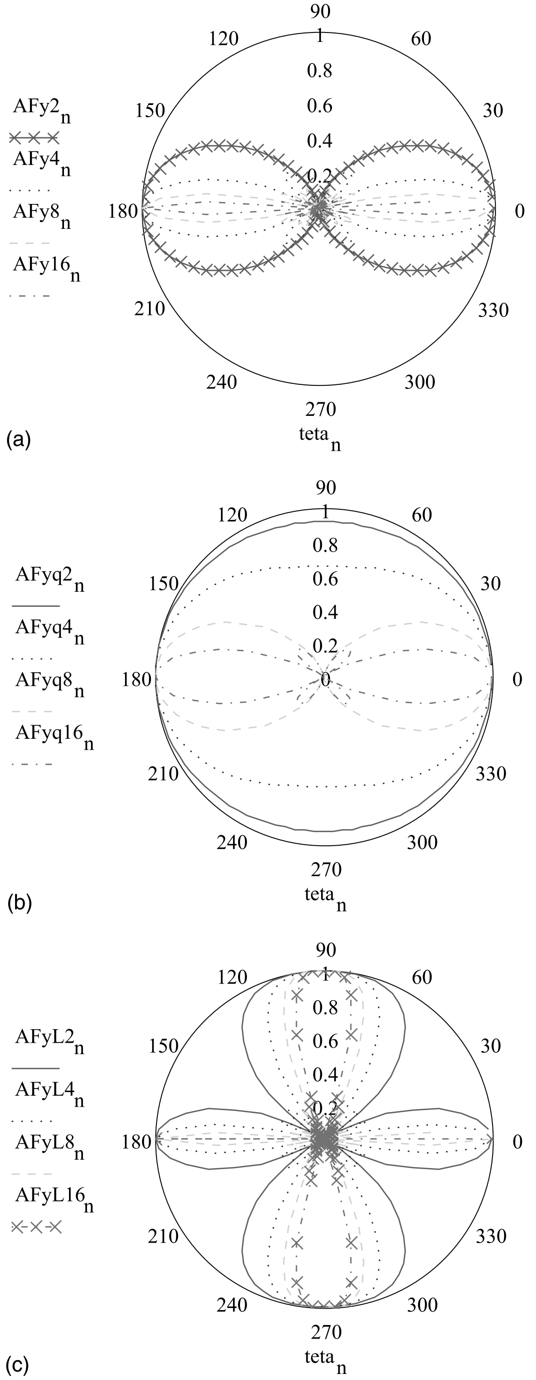

Fig. 1. Beam patterns of the dipole array with a half-wavelength (a), quarter-wavelength (b) and one wavelength (c) separation between the dipoles. Array factors AFy2, AFy4, AFy8, AFy16 correspond to 2, 4, 8, 16 dipoles.

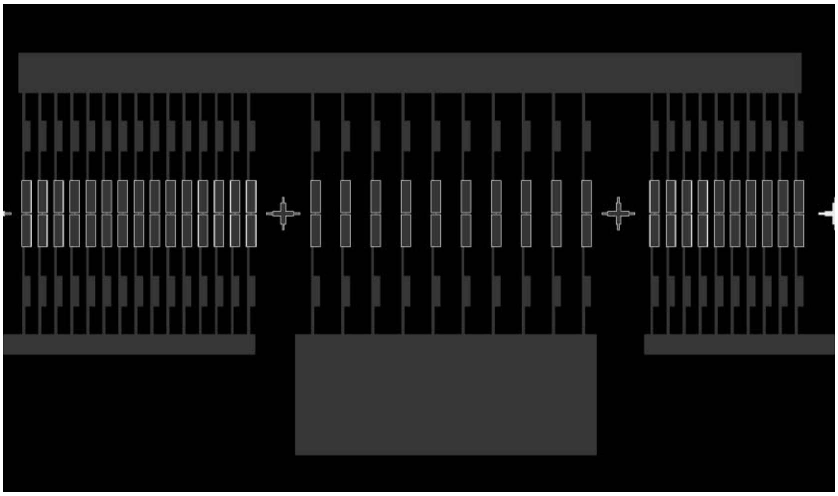

Fig. 2. Layout of the sample which contains the arrays of 162 μm long dipoles at 40, 75 and 40 μm separation and filter structures to avoid the microwave leakage to the feeding bus.

where n_x is the number of elements and $k_d = 2\pi/\lambda_d$. For an array with 16 dipoles separated by $\lambda/2$ the array factor for one direction is

$$\mathrm{AFy16} = \cos\left(\frac{\pi}{2}\sin\theta\right)\cos\left(\frac{2\pi}{2}\sin\theta\right) \times \cos\left(\frac{4\pi}{2}\sin\theta\right)\cos\left(\frac{8\pi}{2}\sin\theta\right). \qquad (2)$$

The result of a numerical calculation of the array factor according to (1) and (2) for 2, 4, 8 and 16 junctions with a dipole (slot) separation of $\lambda/4$, $\lambda/2$ and λ is presented in Fig. 1. A sharpening of the beam pattern is achieved when the separation between junctions is equal to $\lambda/2$. On the other hand, for a λ separation, the main lobe is oriented along the substrate. This effect can be easy explained: radiation perpendicular to the substrate plane is added in-phase at far-field distance since the phase difference becomes negligible there, whereas radiation parallel to the substrate plane is cancelled for $\lambda/2$ separation since the radiation from one junction approaches the next dipole out of phase. As a result of this a rather sharp beam pattern is formed in a plane perpendicular to the substrate. In orthogonal phase the beam pattern is the same as for a single dipole. To demonstrate this concept we designed three types of arrays with the same size of dipoles and different separation between them (Fig. 2). Measurements were performed for the arrays with parallel DC biasing of the elements to demonstrate the phase locking and get rid of the variation in junction parameters.

3. Experimental results

Examples of voltage dependencies of dynamic resistances measured in the temperature range 4–60 K are presented in Fig. 3. Besides the main resonance at 360 GHz, there are also resonances at voltages corresponding to the second and third harmonic and subharmonics at 1/2, 3/2, 5/2 of the main resonant frequency. Shapiro steps (Fig. 4) were observed in the *I–V* curves under external microwave irradiation at 300–500 GHz. Sensitivity to external radiation is an order of magnitude better compared to a single junction. In order to detect oscillations from the JJA we attached another substrate with a planar antenna and a single Josephson junction to the back of the JJA substrate. The main lobe of both the Josephson oscillator and the detector is directed into the dielectric that means that they will be matched if both antennas are placed in front of each other. Such

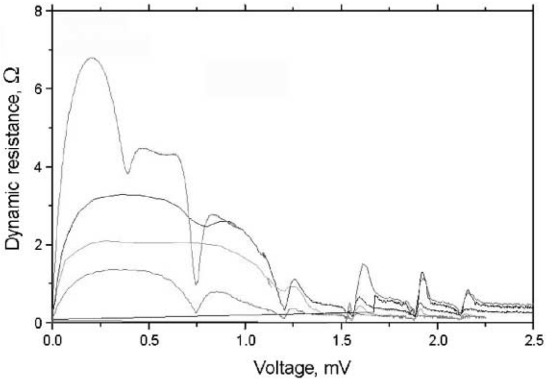

Fig. 3. Dynamic resistance dependence on DC bias voltage of array at different temperatures. Dipole length is 2 × 81 μm, separation is 40 μm, number of dipoles is 15, junction width is 2 μm, deposited on sapphire bicrystal substrate. Measured at temperatures 52, 31, 21, 19, 11 and 4 K (from top to bottom). Minima corresponds to resonant interaction between the dipoles at harmonics of the resonant frequency.

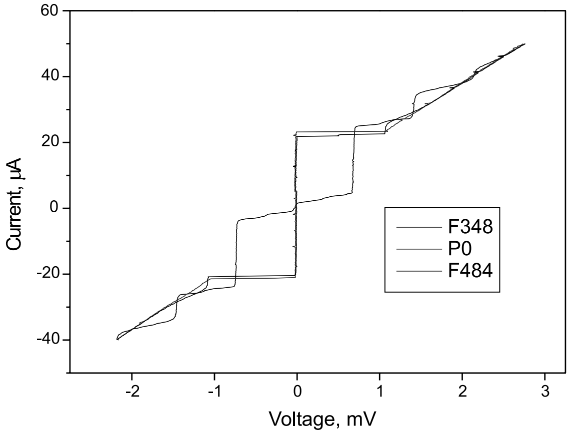

Fig. 4. *I–V* curve of the array on LaAlO bicrystal substrate under microwave irradiation at 348 and 484 GHz.

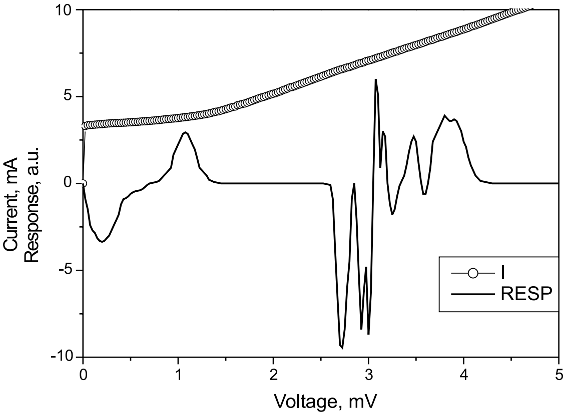

Fig. 5. The dependence of the detector response of the Josephson junction sensor on the Josephson array oscillator bias voltage.

simple quasioptical matching makes it possible to study oscillation spectra in a wide frequency range. Detector response of Josephson detector irradiated by array is presented in Fig. 5. One can see a signal at array bias voltages up to 4 mV that corresponds to an oscillation frequency up to 2 THz. The complicated shape of the detected signal can be explained by the frequency dependence of the oscillator beam pattern as well as resonances between the oscillator and detector substrates.

4. Conclusion

A novel method of phase locking of Josephson junctions by means of a resonant interaction between planar antennas has been proposed, numerically studied and experimentally demonstrated. Parallel arrays of high quality YBaCuO Josephson junctions on a sapphire bicrystal substrate show self-resonant features at the design frequency 350 GHz and its harmonics. The proposed method can be used in Josephson voltage standards, local oscillators in heterodyne receivers, submm-wave detectors.

Acknowledgements

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