QUASI-OPTICAL JOSEPHSON-JUNCTION OSCILLATOR ARRAYS

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Abstract--Josephson junctions are natural voltage-controlled oscillators capable of generating submillimeter-wavelength radiation, but a single junction usually can produce only 100 nW of power and often has a broad spectral linewidth. We are investigating two-dimensional quasi-optical power combining arrays of 10^3 and 10^4 NbN/MgO/NbN and Nb/Al-AlO_x/Nb junction to overcome these limitations. The junctions are DC biased in parallel and are distributed along interdigitated lines. The arrays couple to a resonant mode of a Fabry-Perot cavity to achieve mutual phase-locking. Devices have been produced, and the I-V characteristics of these arrays have been measured, but not as of now in the Fabry-Perot cavity. In this paper, the important features of the design and the critical device properties are discussed.

I. INTRODUCTION

Josephson junctions can oscillate at terahertz frequencies [1], which make them natural candidates for high frequency sources. Unfortunately, a single Josephson junction acting as an oscillator has several significant problems [2]. The maximum output power of a single junction is small

$$P_s \approx 0.4\, I_c\, V_b\,, \qquad (1)$$

where P_s is the source power into a matched load, I_c is the critical current and V_b is the bias voltage). A junction with a critical current of 0.5 mA oscillating at 0.5 THz has a maximum output power of 100 nW. Additionally, the optimum load impedance is typically very small

$$R_L = \sqrt{3}\; V_b \,/\, I_c, \qquad (2)$$

of 3.4 Ω for this example. Because this impedance is so small, it is difficult to optimally couple a single junction oscillator to a typical load. Finally, the linewidth of the oscillation is determined by the low-frequency voltage noise seen by the junction, and it can be quite large,

$$\Delta\nu = \frac{4\pi}{\Phi_0^2}\, R\, k_B\, T, \qquad (3)$$

where $\Delta\nu$ is the linewidth, $\Phi_0 = h/2e$ is the flux quantum and T is the noise temperature ($\approx$ physical temperature for an ideal resistor), and R is the effective resistance seen by the junction at low frequencies. The linewidth is roughly equal to 40 MHz per Ohm per Kelvin. The linewidth can be reduced by shunting the junction with a lower resistance, but this will dissipate more power at 4 K. The linewidth can also be reduced by coupling the junction to a resonant structure, but this may limit the tunability of the oscillator.

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The most obvious use for a Josephson oscillator is to pump an SIS mixer. However, even with the low power requirements of SIS mixers (typically a few μW at 500 GHz), a single junction oscillator is insufficient. In addition, for typical astronomical applications, the output linewidth needs to be small (1 MHz).

If a number of Josephson junctions (N) can be mutually phase-locked, the maximum output power of the array can be N times that of a single optimized junction [2]. In addition, the oscillation linewidth can be reduced, making an array of phase locked Josephson junctions suitable as a local oscillator for SIS mixers. Mutual phase locking typically occurs when part of the power generated by one Josephson junction is shared with the other junctions. This coupling can, under proper conditions, injection-lock the entire array.

The most impressive demonstration of an array oscillator was made by the group at Stonybrook [3]. In their oscillator, 40 resistively shunted tunnel junctions are connected in series at high frequencies with a microstrip transmission line, and in parallel at low frequencies with large inductors. This oscillator was able to generate up to 1.2 μW at a frequencies between 350 and 450 GHz. The linewidth of this oscillator was calculated to be 1 MHz. In their design, the junctions are spaced one wavelength apart on the microstrip line, so the oscillator relies on low-loss propagation on the microstrip line. Therefore, this type of oscillator will probably only work up to the gap frequency of the microstrip line material (730 GHz for niobium), even though the junctions will oscillate up to twice this frequency [1].

II. OSCILLATOR DESIGN

A. Quasi-Optical Slot Array

In our design, we are attempting to use high-frequency electromagnetic coupling in a quasi-optical array. This type of design was used by the Rutledge's group at Caltech in power-combining, transistor oscillator arrays [4]. Wengler has also proposed using quasi-optical grids to couple Josephson junction oscillators [5][6]. The purpose of this design is to mutually phase lock a two-dimensional array of tunnel junctions through quasi-optical coupling of their radiation. The array is situated in a Fabry-Perot cavity to reflect the outgoing radiation back onto the array. The mirrors are analogous to

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backshorts in a waveguide mount, and are used to tune out the junction capacitance. This is a necessary condition, because the junctions must see an inductive impedance for the array to properly phase-lock [2]; this reference deals with series arrays, but the same condition also applies to parallel arrays.

The actual array used differs somewhat from the Rutledge design. The antenna is a set of interdigitated lines periodically bridged by the tunnel junctions. The antenna properties are determined by the spacing of the lines (A), the distance between the junctions along the line (B), the gap between adjacent lines (C), and the dielectric constant of the substrate (ϵ). In our arrays we have $A=20$ μm, $B=140$ μm/70 μm and $C=6$ μm either a silicon ($\epsilon=11.7$) or single crystal quartz substrate ($\epsilon=4.5$). A photograph and scanning-electron micrograph of a 1000 junction NbN array is shown if Fig. 1; the junctions are optically defined.

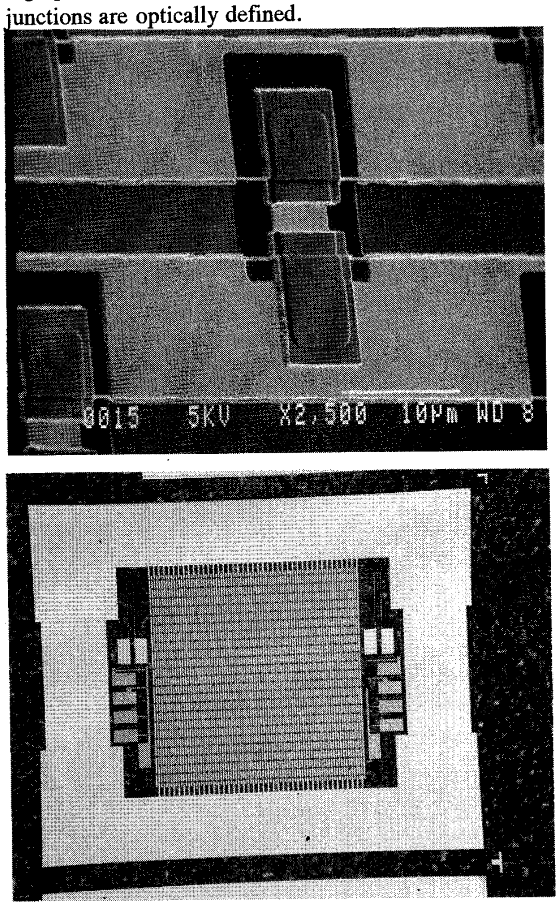

Figure 1. An optical micrograph and SEM of a 1000 junction array.

The impedance of the array was calculated using the method of moments [7] for an array of infinite extent. A plot of the impedance seen by each junction when the array is perfectly phase locked as a function of frequency is shown in Fig. 2. The real impedance is roughly constant up to the

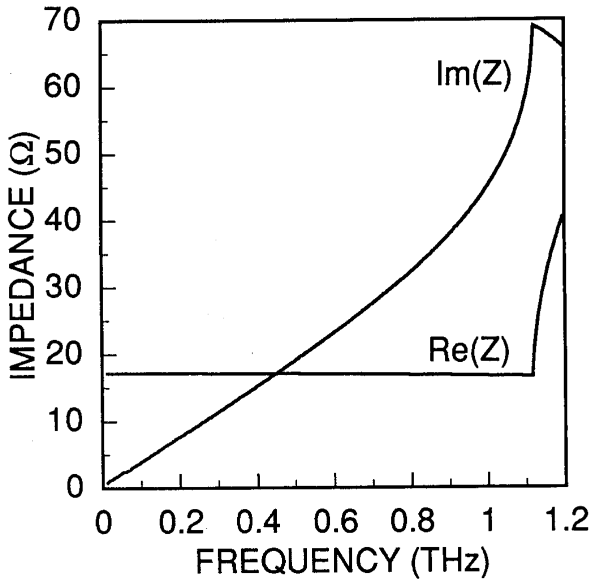

Figure 2. The impedance seen by each junction in a phase-locked array ($A=20$ μm, $B=140$ μm, $C=6$ μm and $\epsilon=4.5$).

frequency of the grating mode for the array (1.12 THz for the case shown), while the reactance grows monotonically. The moment-method calculation can also treat the case in which the array is placed in a Fabry-Perot cavity with mirrors of arbitrary reflectivity.

The array can also be analyzed using a quasi-static model, which is strictly valid in the limit of low frequency. In this model, the junction is connected in parallel to two transmission lines, which represent the plane waves in the air and dielectric. The characteristic impedances of these lines are

$$Z_0^{air} = \frac{377\ \Omega}{(B\ /\ A)}, \qquad Z_0^{diel} = \frac{377\ \Omega}{(B\ /\ A)\ \sqrt{\epsilon}}. \qquad (4)$$

The impedance seen by the junction is these two impedances in parallel,

$$Z_0^{ant} = \frac{377\ \Omega}{(B\ /\ A)\ (1\ +\ \sqrt{\epsilon})} = 17.2\ \Omega, \qquad (5)$$

for our array with an aspect ratio $B/A=7$ on a crystal quartz substrate. As expected, the quasi-static result agrees with the moment calculation perfectly at low frequencies, but it fails to predict the reactance at higher frequencies. However, this simple model allows an intuitive understanding of the effect of placing the array inside a Fabry-Perot cavity. In this case, one terminates the transmission line with short circuits at the appropriated distances from the array. If one of the mirrors is partially reflective in order to serve as an output coupler, the corresponding termination is a small resistance.

Based on these calculations, the ratio B/A should be as large as possible to reduce the antenna impedance; this makes it easier for the Fabry-Perot cavity to tune out the junction capacitance. There are several reasons that the spacing of the lines (A) should be small: the grating mode will be at a higher frequency, the output power per unit area is maximized and the reactive component of the antenna is minimized. The minimum spacing we can obtain with optical lithography is 20 μm with a gap of 6 μm. We have chosen the junction spacing to be 140 and 70 μm to set the grating mode at 1.1 and 2.2 THz on a quartz substrate.

B. Junction DC Bias

The tunnel junctions are DC biased in parallel, which would create a large number of interlocking SQUID loops. The bias currents will flux bias each one of these SQUID loops at a different level. To eliminate this problem, a small series resistor is used with each junction (typically 60 mΩ).

The series resistors also help to mutually phase lock the array. A junction whose phase is ahead of the rest of the array will draw more current, which increases the voltage drop across the series resistor. The sum of the voltage across the resistor and junction is fixed by the potential across the two superconducting bias lines. Thus, when the voltage across the series resistor increases, the voltage across the junction decreases, which decreases the time rate of change of the junction phase ($V=h/2e\ d\phi/dt$) until the phase of the junction equals the phase of the array. This mechanism is sensitive to the uniformity of both the junctions and the series resistors. Experimental measurements of the junction and resistor uniformity will be given in section III.

C. Parallel Shunt Resistor

The linewidth of the oscillation can also be reduced by shunting the array with a cold resistor (see Eq. 3). However, this resistor will dissipate power at liquid helium temperatures, which is undesirable. In our arrays, we have chosen the shunt resistance such that the DC power dissipated in the shunt is roughly equal to the power produced by the oscillator, or roughly $R_p \approx 2R_n$. Because there is significant inductance in series with the shunt resistance, the shunt does not dissipate any RF power. Typically, R_p is in the range 1-10 mΩ, giving a maximum linewidth of 0.16 to 1.6 MHz.

III. FABRICATION AND CHARACTERIZATION

A. Fabrication Process

Two types of oscillators were fabricated. The first used optical lithography and a conventional self-aligned liftoff process to define the junction areas. Both Nb/Al-AlO_x/Nb and NbN/MgO/NbN arrays were fabricated with this process. The optical tunnel junctions were 2 x 2 μm^2, which is the minimum size that can be fabricated with the necessary junction uniformity. The capacitance of these junctions is fairly large (200 and 340 fF for 10 kA/cm^2 Nb and NbN junctions respectively) and their normal state resistance fairly low (5 and 7.5 Ω). This large capacitance may be difficult to tune out with the Fabry-Perot cavity.

In order to reduce the junction capacitance, the device areas were reduced to 1 x 1 μm^2 by using electron-beam lithography. In addition, two junctions were placed in series (one on either side of the slot); this reduced the capacitance (25 and 43 fF) and increased the resistance (40 and 60 Ω) of the effective junction, while reducing the maximum theoretical output power by only a factor of two. At this time, only one wafer of NbN arrays has been fabricated using the e-beam process, but Nb junctions and more NbN junctions will be made in the future.

The trilayers were deposited by DC magnetron sputtering the Nb and NbN films from a Nb target in Ar and Ar-N_2 gases respectively. The base electrodes are typically 200 and 300 nm, and the counter electrodes are typically 100 and 150 nm thick respectively. The Al-AlO_x barriers are deposited by DC magnetron sputtering a thin layer (5 nm) of Al and subsequent thermal oxidation. The MgO barriers are formed by RF magnetron sputtering from a MgO target in an Ar ambient. Pinholes in the barrier are cured by performing a short (1 min.) DC glow discharge in pure oxygen. The trilayers are covered with a thin Au layer (30 nm); this gold layers allows for electrical contact to be made to the devices without ion milling the surface clean.

The fabrication process for both Nb and NbN junctions is similar [8]. The optical junctions were patterned using an AZ 5206 photoresist pattern and RIE in a CCl_2F_2-CF_4-O_2 mixture [9]. The junctions were electrically isolated by evaporating SiO and lifting off the photoresist stencil. For the e-beam devices, a Cr mask was lifted off using PMMA. The Cr pattern was transferred to a polyimide layer using an oxygen RIE process. The Cr/polyimide stencil replaces the photoresist pattern used in the optical process.

As discussed in the next subsection, the uniformity of the series resistors important. To optimize the resistor uniformity, the resistors are deposited before the wiring layer. The series resistors are contacted by the wiring electrode, which is sputter deposited and defined by RIE. Because this RIE step is anisotropic, the edge of the wiring layer is quite vertical; therefore, the resistors must be deposited first, because they are thin (typically 100 nm) and would not adequately cover the edge of the wiring layer.

B. Device Uniformity

The tunnel junctions and series resistors must be fairly uniform for the array to phase lock. However, simulations of phase locking in parallel arrays predict good phase-locking even for 20 % (1 σ) nonuniformities in both I_c and R_s. To determine process yield and uniformity, each oscillator chip has several diagnostic devices, including test resistors and series arrays of 78 tunnel junctions. The fractional standard deviation of the resistors across a 2" wafer is typically 3%. The fractional standard deviation of the critical current for the optical junctions is typically 4%, while for the e-beam junctions it is 8% for the best series arrays. Measurements of series arrays on other masks indicate that the fractional standard deviation of the critical currents in the e-beam junctions should be at most 5% leading us to believe that better e-beam oscillators will be available in the future.

The junction capacitances must also be fairly uniform for the array to phase lock, because the embedding impedance of each junctions must be inductive for it to phase lock. Detailed calculations have not been performed yet, but crude estimates indicate that the fractional deviation of the junction capacitance must be better than roughly $(2\pi f Z_0 C)^{-1}$, where f is the oscillation frequency, C is the junction capacitance, and Z_0 is the characteristic impedance of the transmission line in the equivalent circuit (for quartz, $Z_0 \approx 25\ \Omega$). If we consider an operating frequency of 500 GHz, the uniformity would have to be better than 5 (20) % for a capacitance of 200 (50) fF.

C. Oscillator Array Measurements

The measurement setup for testing the arrays in the Fabry-Perot cavity has not been completed at this time. We have measured the I-V characteristics of the arrays without the cavity, and also with a superconducting mirror deposited on the backside of the substrate. One example of an I-V characteristic of this type is shown in Fig. 3. If the arrays are phase locking, we expect to see an I-V characteristic similar to that of a single junction connected to a microstrip line resonator. None of the arrays tested thus far have shown a strong indication of phase locking. However, only one e-beam wafer has been fabricated and the uniformity of the junctions in that case was not optimal.

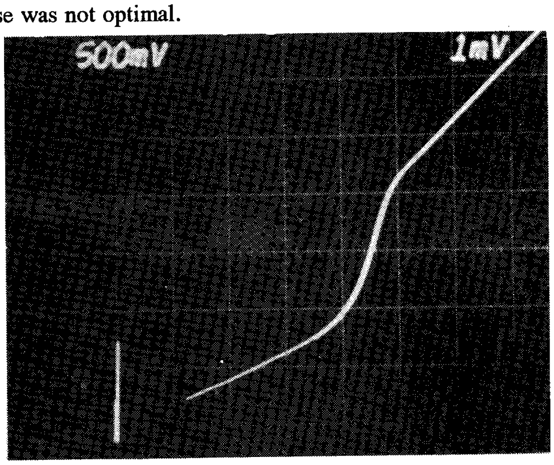

Figure 3. An I-V Characteristic of a 2000 junction NbN array with optically defined junctions. The vertical scale is 200 mA/div and the horizontal scale is 1 mV/div.

IV. CONCLUSIONS AND FUTURE WORK

We have designed and fabricated quasi-optical arrays of Nb and NbN tunnel junctions which should oscillate in the 100 GHz to 2 THz frequency range. The array configuration we are using has a relatively low impedance, which should allow the capacitance of the junctions to be tuned out at the oscillation frequency. The optically defined arrays were successfully fabricated, while only the first set of e-beam defined junctions have been fabricated and they had worse than expected uniformity. Future work will include testing of these devices in a tunable Fabry-Perot cavity and the fabrication of more e-beam defined arrays.

V. ACKNOWLEDGEMENTS

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