Design of high-frequency, high-power oscillators using Josephson-junction arrays

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Abstract. We analyze the limitations imposed by junction capacitance and the parasitic inductance associated with shunt resistors on the performance of Nb/Al-AlO₃/Nb-junction-array oscillators. We use wide junctions that are in situ deposited on top of PdAu resistor films (to minimize inductance) and are situated above Nb ground planes to ensure uniform current injection. From the measured parasitics, we infer the maximum power and frequency that can be obtained for critical-current densities \( J_c \leq 100 \, \text{kA/cm}^2 \). We illustrate these findings with experimental results of a 1,968-junction-array having \( J_c = 10 \, \text{kA/cm}^2 \) that was found to couple 0.1 - 0.8 mW to a 56-Ω load in the range 100-300 GHz.

1. Introduction

The operation of high-frequency oscillators based on arrays of \( N \) resistively-shunted Josephson tunnel junctions is limited by the junction capacitance \( C \) and the parasitic inductance \( L \) associated with the shunt resistor \( R \). Arrays with critical-current nonuniformity but without these parasitics have been shown through simulations to phase lock and emit coherent power when coupled to matched load resistors \( R_L = NR \) [1]. The junction parasitics limit the maximum array operating frequency \( f_{op} \) to the LC-resonance frequency \( f_{LC} = \frac{1}{2\pi\sqrt{L_C/C}} \), while the onset of phase locking usually occurs near the characteristic frequency \( f_c = \frac{2\pi}{R\Phi_0} \) for arrays with or without parasitics; \( I_c \) is the junction critical current and \( \Phi_0 = h/2e \) is the magnetic-flux quantum.

The dynamics of a single junction have been shown to be unstable for large inductance parameter \( \beta_L = 2\pi L I_c/\Phi_0 \) [3]. For small inductance, \( \beta_L < 0.7 \) and any \( \beta_L = 2\pi I_c R^2/C \Phi_0 \), or \( \beta_L < 1.5 < \beta_L < 1 \), stable periodic-1 junction oscillations occur at all voltages. Our experiments indicate that the phase-locked state is still limited to \( f_{op} < f_{LC} \) [2].

Our oscillator designs focus on minimizing \( L \) so that the power \( P = I_c^2 R \) delivered to a 50-Ω matched load is maximized. Our goal is to generate milliwatt power levels at frequencies above 300 GHz as compared with the previous record of -50 mW [4]. We focus on the design criteria for oscillators based on distributed and lumped series arrays given existing fabrication technology, and illustrate these findings with an experiment in which -0.8 mW was coupled from a 1,968-junction distributed array to a 56-Ω load near 240 GHz.

2. Design and Fabrication

In order to optimize \( P \), \( I_c \) needs to be maximized. \( I_c \) is usually limited by self-field effects; however, a junction with uniform bias-current injection (which is ensured by placing the junction above a superconductive ground plane (GP) or by using bias resistors) can achieve \( I_c = I_{JG} \tau \) even when \( \tau \gg \lambda_J \), the Josephson penetration depth. The junction's length and width are \( l_J \) and \( w_J \), respectively. We believe that resonances in the Nb/Al-AlO₃/Nb-junction barrier [5], which result in spatial phase variations along \( w_J \) and thereby reduced \( P \), can be prevented through damping when \( \beta_L \leq 0.7 \).

Fig. 1: (a) Top view and (b) cross section of two shunted junctions. Current is injected from left to right.

Our array designs maximize \( I_c \) through \( w_J \) and minimize \( L \) by maximizing the width of the PdAu resistors (RS) \( w_{RS} \) to \( w_J \); the junctions are in situ deposited on top of the RS layer (see Fig. 1). \( L \) is determined by the loop that is formed from the counter electrode (CE) to the windows in the junction-isolating, 300-nm-thick SiO₂ (S2) layer [6]. The shunt resistors are patterned with a wet etch and extend under each 'lumped' group of junctions. Reactive-ion etches of the Nb base electrode (BE) and CE respectively define an estimated resistor length \( \ell_R \approx 1.6 \, \mu\text{m} \) and \( l_J \approx 1.4-2 \, \mu\text{m} \), respectively. The inductive length \( \ell_L \) of the resistor is \( \approx 2.6 \, \mu\text{m} \). These are the lengths that we have fabricated.

Figure 2a shows junction specific capacitance \( C_J \) (in pF/µm²) as a function of \( I_c \) (in kA/cm²) which we deduced from SQUID- and wide-junction-resonance data. The plasma
If we fix $\beta_0$ to a maximum of 1, we obtain $l_c (= l_{fsa})$ and thereby $P (= l_{fsp})$ as a function of $f_{op} = f_c$, this plotted in Fig. 2b. $R (= f_{op} \phi)$ since $f_{op} = f_c$, the PdAu sheet resistance $R_{s} (= f_{op})$, and $\phi (= 1/f_{sp})$ are adjusted for each $f_{op}$. Requiring $\beta_s \leq 1$ determines the minimum $L_c$ and maximum $l$ that can be used since $f_{op} = f_c$. Figure 2b shows that milliwatt power levels can be obtained with distributed arrays, but that such-micrometer junction lengths are required for $f_{op} > 400$ GHz. Contacts to sub-micrometer CEs require planarization of the S2 layer which further reduces $L$ and $\beta_s$, and increases $f_{op}$.

A similar analysis can be performed for 'lumped' arrays, that is, arrays with length $\leq \lambda/4$. This is of interest for the application of voltage-and, power-tunable arrays [7] as local oscillators for (arrays of) on-chip SIS mixers with $R_{l} = 20 \Omega$. Since $NR \ll R_{l}$, only part of the available power is delivered to the mixer, $-4 \mu W$ for case (1), and $-10 \mu W$ for case (2), for $f_{sp} > 500$ GHz, see Fig. 2c. However, this impedance mismatch will prevent losses in the Nb striplines from determining the delivered power since the total surface resistance will be $<< R_{l}$ for frequencies below the Nb gap frequency.

Our distributed arrays are designed with $f_{l} < f_{op} < f_{sc}$ and $w_{ks} = 85 \mu m ($$< \lambda/4$) so that $L = 20 \Omega$. The 24-junction groups (within 152 $\mu m$) are centered to-center spaced by $\lambda/2 = 272 \mu m$. The array is connected in a loop with the load resistor (with $R_{l} = 10 \Omega$) and a detector junction; the array is separated from the load and detector by two 48 $\times$ 85 $\mu m^2$ dc-blocking stripline capacitors (of 0.6 $pF$) on either end of the array. The junctions have $J_c = 11 kA/cm^2$ and $l = 1 \mu m$; the latter $l_c$ with $f_{sp} = 200$ GHz gives $\beta_{s} = 1$ and $\beta_{l} = 0.44$.

3. Results and Conclusions

Figure 2d shows a detector I-V curve when the array is emitting at $f_{op} = 240$ GHz [8]. From the measured amplitude of the simulated detector I-V curves (including parasitics), we estimate an r-f current $I_{rf} = 5.5 \pm 0.5$ mA, so that the power dissipated in the 56-$\Omega$ load resistor at 240 GHz is: $P = I_{rf}^2 R_{l} = 0.85$ mW. At half the operating frequency $f_{sp}/2$, we have detected a power of $<< 0.4$ mW when the junction groups are separated by a quarter-wavelength. This array also delivers $>100$ $\mu W$ (which corresponds to a 2-nA Shapiro step) at most frequencies in the 100 GHz to 300 GHz range. These encouraging result suggest that milliwatt powers can be obtained.

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References