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

P A A Booi and S P Benz

National Institute of Standards and Technology, Boulder, Colorado 80303, U. S. A.

Abstract. We analyze the limitations imposed by junction capacitance and the parasitic inductance associated with shunt resistors on the performance of Nb/Al-AlO$_x$/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 $J_c \leq 100$ kA/cm^2. We illustrate these findings with experimental results of a 1,968-junction array having $J_c \approx 10$ 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 $f_{LC} = \Phi_0/(2\pi\sqrt{LC})$, while the onset of phase locking usually occurs near the characteristic frequency $f_c = I_c R/\Phi_0$ [2] 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 $\beta_c = 2\pi I_c R^2 C/\Phi_0$, or $\beta_L \leq 1$ and $0.5 < \beta_c < 1$, stable period-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 minimization of L so that the power $P \approx I_c^2 R_L/8$ 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 μW [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 $I_c = J_c l_j w_j$ even when $w_j \gg \lambda_J$, 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-AlO$_x$/Nb-junction barrier [5], which result in spatial phase variations along w_j and thereby reduced P, can be prevented through damping when $\beta_c \leq 0.7$.
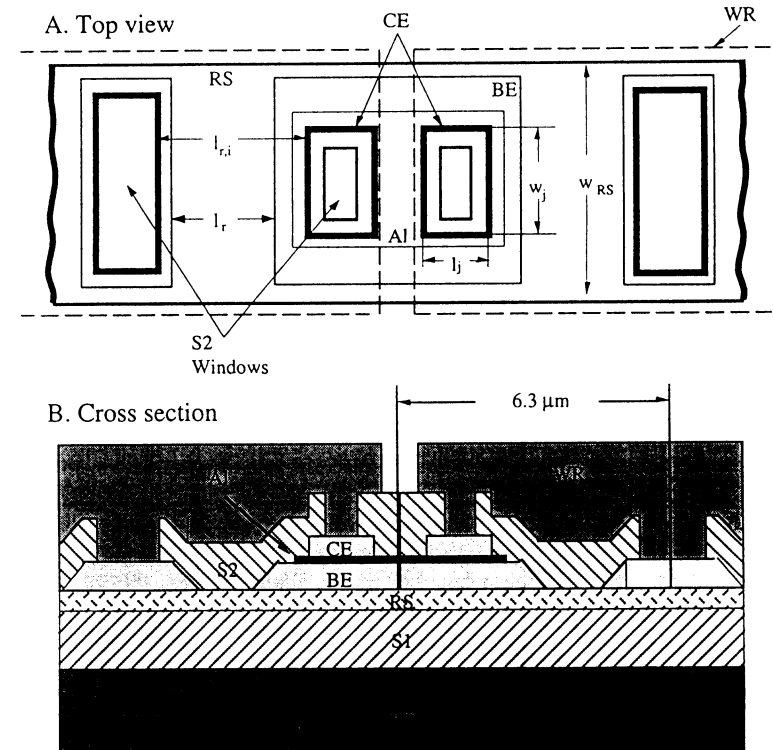

Fig. 1: (a) Top view and (b) cross section of two shunted junctions. Current is injected from left to right.

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 SiO$_2$ (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 l_r of ~1.6 μm and l_j of 1.4-2 μm, respectively. The inductive length $l_{r,i}$ of the resistor is ~2.6 μm. These are the lengths that we have fabricated.

Figure 2a shows junction specific capacitance C_s (in fF/μm^2) as a function of J_c (in kA/cm^2) which we deduced from SQUID- and wide-junction-resonance data. The plasma

frequency $f_p = 877 \sqrt{J_c C_s}$ GHz $= f_c/\beta_c^{1/2}$ [or approximately $f_p = 133 (J_c)^{0.37}$ GHz in Fig. 2a] determines the maximum f_c that can be obtained while keeping the junction's current-voltage (I-V) characteristic non-hysteretic ($\beta_c \leq 0.7$).

In designing these oscillators, we must choose a maximum w_{RS}. We have limited w_{RS} and the Nb wiring (WR) width in our designs to $\leq \lambda/4$, where λ is the wavelength at f_{op}. However, one can also use $w_{RS} = \lambda/2$ as this defines the maximum width for which no higher-order stripline modes occur. We believe that we may be able to reduce l_r to 0.6 μm and $l_{r,i}$ to 1 μm when our photo-lithography process is fully optimized. Thus, we have defined two limiting cases for our array designs: (1) $l_{r,i} = 2.6$ μm and $w_{RS} = \lambda/4$, which is our present fabrication process, and (2) $l_{r,i} = 1$ μm and $w_{RS} = \lambda/2$, which is achievable.

If we fix β_L to a maximum of 1, we obtain I_c ($\propto 1/f_{op}$) and thereby P ($\propto 1/f_{op}^2$) as a function of $f_{op} = f_c$; this is plotted in Fig. 2b. R ($\propto f_{op}^2$ since $f_{op} = f_c$), the PdAu sheet resistance R_s ($\propto f_{op}$), and N ($\propto 1/f_{op}^2$) are adjusted for each f_{op}. Requiring $\beta_c \leq 1$ determines the minimum J_c and maximum l_j that can be used since $f_{op} = f_p$. Figure 2b shows that milliwatt power levels can be obtained with distributed arrays, but that sub-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 β_L, and increases f_{op}.

A similar analysis can be performed for 'lumped' arrays, that is, arrays with length $< \lambda/4$. 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 μW for case (1), and ~10 μW for case (2), for $f_{op} > 500$ 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 $\ll R_L$ for frequencies below the Nb gap frequency.

Our distributed arrays are designed with $f_c < f_{op} < f_{LC}$ and $w_{RS} = 85$ μm ($< \lambda/4$) so that $L \approx 20$ fH. The 24-junction groups (within 152 μm) are center-to-center spaced by $\lambda/2 = 272$ μm. The array is connected in a loop with the load resistor (with $R_s = 10\ \Omega$) and a detector junction; the array is separated from the load and detector by two 48×85 μm^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 $l_j = 2$ μm; the latter l_j with $f_c = 200$ GHz gives $\beta_L \approx 1$ and $\beta_c \approx 0.44$.

3. Results and Conclusions

Figure 2d shows a detector I-V curve when the array is emitting at $f_{op} = 240$ GHz [8]. From a comparison of the measured and simulated detector I-V curves (including parasitics), we estimate an rf-current amplitude $I_{rf} = 5.5 \pm 0.5$ mA, so that the power dissipated in the 56-Ω load resistor at 240 GHz is: $P = I_{rf}^2 R_L/2 \approx 0.85$ mW. At half the operating frequency $f_{op}/2$, we have detected a power of ~0.4 mW when the junction groups are separated by a quarter wavelength. This array also delivers >100 μW (which corresponds to a 2-mA 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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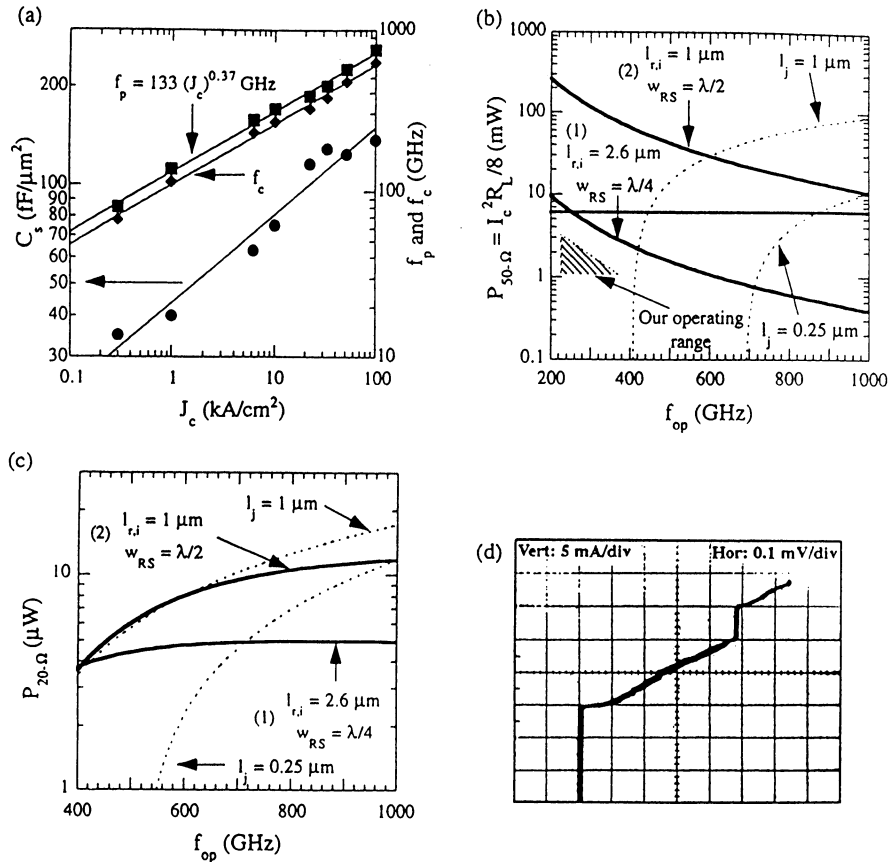Fig. 2: (a) Measured C_s (circles), f_p (squares) and f_c (diamonds) (for $\beta_c = 0.7$) as a function of J_c; solid lines are least-square power fits. (b) and (c) respectively show the power (solid lines) that *distributed* and *lumped* arrays with $\beta_L = 1$ can deliver to either a matched 50-Ω load, or a 20-Ω load as a function of $f_{op} = f_c$. Requiring $\beta_c = 1$ [$f_{op} = f_p$, see (a)] determines l_j as illustrated with the dashed lines. We indicate the power at which the chip will heat above T_c (with a ~6-% oscillator efficiency when $f_{op} = f_c$) with the horizontal line. (d) Detector I-V curve displaying a ~5 mA Shapiro step near 240 GHz; the current axis has a 5-mA off set.

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