High Power Submillimeter Wave Source using Series Biased Linear Josephson Effect Array

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As millimeter and submillimeter sources, phase-locked array of N Josephson junctions can overcome many shortcomings of the single junction source such as low source impedance, low output power, and large linewidth. In recent years it has been demonstrated that small linear arrays ($N \leq 100$) are capable of delivering several μW power to a load of 10 to 60 Ω in the frequency range of ~ 200 GHz to ~ 600 GHz with linewidth $\Delta f/f < 5 \times 10^{-6}$ [1-4]. For many applications one would like to have higher power and narrower linewidth which can be achieved by increasing the number of junctions deployed in the array since the output power increase as N^2 and linewidth decreases as $1/N^2$ for arrays having $NR_J = R_L$, where R_J and R_L are the junction's shunt resistance and the load resistance, respectively. There are two basic designs for the medium size ($N \sim 10^2$) and large size ($N \sim 10^3$) linear Josephson array: the quasi-lumped array and distributed array [4, 5]. In a quasi-lumped array the distance between two adjacent junctions is λ_0 (wavelength at designed operating frequency). In a distributed array a group of m junctions are closely packed together and the distance between two adjacent groups is λ_0. In both types of array the junctions are embedded in the transmission line structure which provides the long-range high-frequency electromagnetic couplings between the junctions. This coupling is essential to achieve mutual phase locking in the linear array. Compared to the quasi-lumped array, the distributed array requires less space and has smaller internal rf loss (especially as f_0 approaches the superconducting gap frequency of ~ 700 GHz for Nb).

The output rf power coupled to a load R_L from an linear array of N junctions can be written as

$$P_N = \frac{(\gamma N V_c)^2 R_L}{2(NR_J + R_L)^2} \tag{1}$$

when the source impedance matches to the load Eq. (1) becomes

$$P_N = \frac{(\gamma N V_C)^2}{8 R_L} \tag{2}$$

where $V_C \equiv I_C R_J$ is the characteristic frequency of the junction, I_C is the critical current of the junction. γ depends on the dc bias voltage and is usually less than unity.

We have designed medium size ($N = 500$) distributed array ($m = 10$) oscillators for operation around 400 GHz. Each resistively shunted Nb/AlO/Nb tunnel junction is 5.2 $\mu\mathrm{m}^2$ in size and has designed parameters of $I_C = 1.4$ mA ($J_C = 27000$ A/cm^2) and $R_J = 0..5\ \Omega$ which give $V_C = 0.7$ mV, $\beta_C \equiv 2\pi V_C R_J C_J / \Phi_0 \simeq 0.25$ and $\beta_L \equiv 2\pi I_C L_S / \Phi_0 \simeq 0.8$, where C_J and L_S are the shunt capacitance of the junction and the parasitic inductance associated with the shunt resistor, respectively. Φ_0 is the flux quantum. The total length of the array is about 50 λ_0 (at ~ 400 GHz). The Nb microstrip line is 250 nm thick and 8 μm wide with 670 nm thermally evaporated SiO between the microstrip line and the 340 nm thick Nb ground plane. This gives $Z_0 \simeq 12\ \Omega$. The designed output power to the 50 Ω load is about 100 μW around 400 GHz.

The Nb/AlO/Nb trilayer films were made at AT&T Bell Laboratory and the arrays were fabricated at IBM using the PARTS process developed by Ketchen et. al [6]. The measured parameters of a typical single junction from wafer #8 are $I_C = 2.5$ mA, $R_J = 0.56\ \Omega$ and $V_C = 1.4$ mV at 4.2 K. This corresponding to a Jc of about 50000 A/cm^2 which is about twice of the designed value. This results in a value of $\beta_C \simeq 0.56$ and $\beta_L \simeq 1.6$ which are quite far away from the designed value and unfavorable for phase-locking. The measured load resistance is 62 Ω.

The output rf power to the load resistor has been measured using the on-chip Josephson junction detectors. The amplitude of the rf current through the detector junction is estimated by comparing the size of the first Shapiro step and the suppression of the critical current to those obtained from the numerical simulations using measured V_C, I_C, and R_J. The estimated output rf power P_{rf} is 45 ± 15 μW using the suppression of I_C and is 50 ± 25 μW using the size of the first Shapiro step. The measured rf power is consistent with $P_{rf} = 65$ μW calculated from Eq. (1) [7]. The measurement of the output power spectrum $P_{rf}(f)$ is currently in progress.

In summary, a linear Josephson effect array oscillator with series dc bias has been designed to deliver rf power of about 100 μW to a 50 Ω load. The measured output power to the 62 Ω load at $\sim$400 GHz is 50 μW, lower than designed value., due to the difference between the target critical current and that of the sample.

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[7] In deriving Eq. (1) it is assumed the junctions can be approximated well by the RSJ model. However, this condition is not met by the junctions used in this work. Thus Eq. (1) can be used only to give a rough estimate of P_{rf}.