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

Siyuan Han, Baokang Bi, Wenxing Zhang, A. H. Worsham, and J. E. Lukens
Department of Physics, SUNY at Stony Brook
Stony Brook, NY 11794, U.S.A.

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 \( \mu \)W power to a load of 10 to 60 \( \Omega \) in the frequency range of \( \sim 200 \) GHz to \( \sim 600 \) 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 \( \lambda_0 \) (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 \( \lambda_0 \). 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 \( \sim 700 \) GHz for Nb).

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

\[
P_N = \frac{(\gamma NV_C)^2 R_L}{2(NR_J + R_L)^2}
\]
when the source impedance matches to the load Eq. (1) becomes

$$P_N = \frac{(\gamma NV_C)^2}{8R_L}$$

(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. $\gamma$ 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 $\mu$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, $\beta_c = 2\pi V_C R_J C_J/\Phi_0 \approx 0.25$ and $\beta_L \equiv 2\pi I_C L_S/\Phi_0 \approx 0.8$, where $C_J$ and $L_S$ are the shunt capacitance of the junction and the parasitic inductance associated with the shunt resistor, respectively. $\Phi_0$ is the flux quantum. The total length of the array is about $50 \lambda_0$ (at $\sim 400$ GHz). The Nb microstrip line is 250 nm thick and 8 $\mu$m wide with 670 nm thermally evaporated SiO between the microstrip line and the 340 um thick Nb ground plane. This gives $Z_0 \approx 12$ $\Omega$. The designed output power to the 50 $\Omega$ load is about 100 $\mu$W 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 $J_C$ of about 50000 A/cm$^2$ which is about twice of the designed value. This results in a value of $\beta_c \approx 0.56$ and $\beta_L \approx 1.6$ which are quite far away from the designed value and unfavorable for phase-locking. The measured load resistance is 62 $\Omega$.

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 $45 \pm 15$ $\mu$W using the suppression of $I_C$ and is $50 \pm 25$ $\mu$W using the size of the first Shapiro step. The measured rf power is consistent with $P_{rf} = 65$ $\mu$W 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 \( \mu \text{W} \) to a 50 \( \Omega \) load. The measured output power to the 62 \( \Omega \) load at \( \sim 400 \) GHz is 50 \( \mu \text{W} \), 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 \( P_{\text{rf}} \).