

- [22] Y. Yiquan and S. Shoupeng, "PVDF-DMOS transducer for underwater acoustic imaging," *Appl. Acoust.*, vol. 4, no. 3, pp. 25–29, July 1985.
- [23] Y. Yiquan and Z. Wenhui, "Directivity of polyvinylidene fluoride layered structure transducer," *J. Nanjing Inst. Technol.*, no. 1, pp. 81–87, 1985.
- [24] D. G. Shombert, S. W. Smith, and G. R. Harris, "Angular response of miniature ultrasonic hydrophones," *Med. Physics*, vol. 9, no. 4, pp. 484–492, 1982.
- [25] Y. Yiquan, S. Yaomei, S. Binwen, "PB-I Type narrow pulse piezoelectric polymer reversible transducer," *Appl. Acoustics*, vol. 6, no. 1, pp. 25–31, Jan. 1987.
- [26] Y. Yiquan, "The performance and applications of PZT composite transducer with 3-3 connectivity," *IEEE Trans. Ultrason., Ferroelect., Freq. Cont.*, vol. 38, no. 6, pp. 712–714, Nov. 1991.

High-Frequency Oscillators Using Phase-Locked Arrays of Josephson Junctions

S. P. Benz and P. A. A. Booij

Abstract—We present a basic description of Josephson junctions and discuss their use as GHz and THz oscillators. The resistively shunted junction model is used to calculate the available power, linewidth, and operating frequency of the oscillators. We discuss how phase-locked arrays of junctions are used to achieve higher power and narrower linewidth. Two experimental examples of phase-locked emission are shown: one from on-chip detection circuits at 150 GHz and one detected off-chip showing a 13-kHz linewidth at 88.8 GHz.

I. INTRODUCTION

We are interested in developing the technology to synthesize and measure sub-THz and THz frequencies with the same ease and precision now available in the microwave region. This is important for bridging the frequency band between the microwave and optical regions. This effort is intended to support and encourage emerging instrumentation in high-speed optical signal processing and precision optical metrology including standards for frequency and length.

We believe this frequency band can be filled by exploiting the intrinsic high-frequency properties of superconductive Josephson-junction devices. Josephson junctions and circuits are naturally suited to sub-THz and THz frequency operation because they intrinsically generate currents at frequencies up to a few times the gap frequency of the superconducting material. Low-temperature superconductor (LTS) devices are typically made from Nb, a refractory metal with a superconducting transition temperature T_c of 9 K and are operated at 4 K. Nb junctions have a gap frequency of about 1.4 THz. LTS devices have been demonstrated to operate at 8 THz [1]. High-temperature superconductor (HTS) devices, such as YBaCuO, have $T_c \approx 90$ K, allowing 77 K liquid nitrogen operation. HTS devices have demonstrated operation at 8 THz, [2] and with a gap frequency of approximately 15 THz, are expected to perform frequency translation functions up to at least 30 THz.

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By developing small, lithographically-fabricated devices based on Josephson junctions, we hope to achieve an unprecedented level of stability and reliability over previous technologies based on gas lasers and whisker-contacted diodes. Lithography also enables the integration of multiple devices into circuits in order to perform more complex frequency translation functions. LTS fabrication technology is well-developed. However, HTS multilayer thin-film fabrication is still under development.

Many different devices can be implemented using Josephson technology, such as mixers, oscillators, detectors, and logic elements. This correspondence will focus on Josephson oscillators and their application to the submillimeter (>300 GHz) and THz frequency regimes. We present experimental results from LTS devices that were designed to demonstrate the fundamental principles of Josephson oscillators at accessible microwave frequencies.

II. PRINCIPLES OF JOSEPHSON OSCILLATORS

We use the zero-capacitance, resistively-shunted junction (RSJ) model [3], [4] to compare Josephson oscillators based on single junctions and arrays of junctions. Our discussion will be limited to nonresonant junctions, so no comments will be made on flux-flow oscillators [5]. Furthermore, we assume lumped arrays having physical dimensions smaller than $1/8$ of the emission wavelength. Finally, we assume that ground planes are used with all circuits, preventing self-field coupling between devices. Within this model, we discuss specific design criteria required to achieve impedance matching, high output power, and narrow linewidth at a given operation frequency.

A. Single Junctions

A RSJ is characterized by a critical current I_c and resistance R and is biased with a dc current source I . The equations describing a RSJ are

$$I = \frac{\Phi_0}{2\pi R} \dot{\phi} + I_c \sin \phi \quad (1a)$$

$$V = \frac{\Phi_0}{2\pi} \ddot{\phi} \quad (1b)$$

where $\phi(t)$ is the macroscopic phase difference across the junction, $\Phi_0 = h/2e \approx 2.07$ mV/THz is the magnetic flux quantum, V is the instantaneous voltage across the junction, and the overdot denotes differentiation with respect to time.

Equation (1) can be solved analytically. Fig. 1(a) shows the dc I - V curve of a RSJ. For $I \leq I_c$, the junction is in the zero-voltage state, while for $I > I_c$, a voltage develops across the junction. In the voltage state, the supercurrent $I_c \sin \phi$ of a junction oscillates at a well-defined fundamental frequency $f = V_{dc}/\Phi_0$. This *ac Josephson effect*, where the junction supercurrent oscillates at $1/\Phi_0 \approx 483$ GHz per mV of bias voltage, means that the junction is intrinsically a high-frequency dc-to-ac converter and can be used as a voltage-controlled oscillator.

Fig. 1(b) shows the amplitude of the fundamental Josephson oscillation and the first two higher harmonics as a function of voltage. When the junction is biased at voltages greater than the characteristic voltage $V_c \hat{=} I_c R$, the time-dependent voltage is nearly sinusoidal because the amplitudes of the higher harmonics V_n ($n \geq 2$) are much smaller than the amplitude of the fundamental. The peak voltage amplitude at the fundamental frequency approaches a maximum $V_1 \approx V_c$ for $V_{dc} \geq V_c$, and the junction impedance becomes

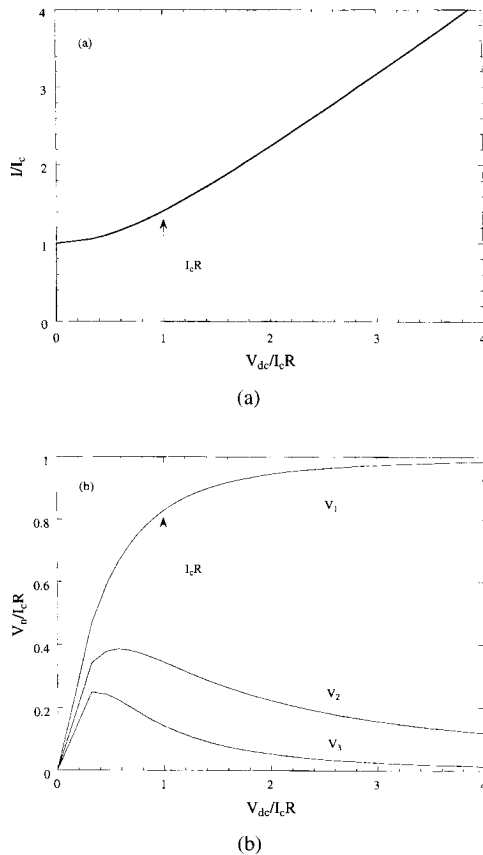


Fig. 1. (a) I - V curve of a RSJ. (b) Harmonic amplitudes V_n as a function of bias voltage.

resistive, $Z \approx R$. In order to maximize the fundamental power and minimize the contribution from harmonics, the characteristic frequency, $f_c = V_c/\Phi_0$ should be fixed at the minimum operating frequency, and the device should be operated at $V_{dc} \geq V_c$. Under these conditions, the *rms available power* from the junction is

$$P_{JJ} = \frac{V_c^2}{8R} = \frac{I_c V_c}{8}. \quad (2)$$

If we assume that all Josephson junction technologies have a maximum critical current, then the available power is limited by the maximum I_c and the minimum operating frequency. Typically it is assumed that I_c is limited to a few milliamperes by nonuniform current flow due to self-induced magnetic fields [6]. The characteristic voltage is limited for a given technology by the gap frequency of the superconducting material. Typical Nb junctions have a maximum characteristic voltage $V_c \approx 2.8$ mV. Under these *optimal* conditions, the available power from a single junction could approach $P_{JJ} \approx 1$ μ W for operation above 1.4 THz. Lower minimum operating frequencies will yield lower power.

If the junction is coupled to a resistive load R_L and $V_{dc} > V_c$, the most efficient power transfer occurs when the junction and load resistances are matched ($R = R_L$). The rms power delivered to this *matched load* is then equal to the available power. Demanding $R_L = 50$ Ω load and $f_c = 1.4$ THz limits the critical current to only $I_c = V_c/R_L = 58$ μ A. The power delivered to a matched 50 Ω load for this example is only 20 nW. In the highest frequency demonstration of a single junction Josephson oscillator, a tunnel junction delivered 10 nW at 1 THz to another junction on the same chip [7].

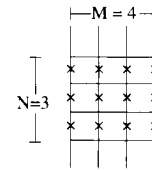


Fig. 2. Schematic layout of a 4×3 array. The crosses depict Josephson junctions. The junctions are connected by superconducting wires with inductance.

Many oscillator applications require linewidths < 100 kHz. The theoretical linewidth (full width at half-maximum power) at the fundamental frequency for a single junction is [8], [9]

$$\Delta f_{JJ} = \frac{\pi R_d^2 S_I(0)}{\Phi_0^2} \approx \left(\frac{41 \text{ MHz}}{\Omega \text{K}} \right) \frac{T R_d^2}{R} \quad (3)$$

where $R_d = dV_{dc}/dI$ is the dynamic resistance of the junction, $S_I(0) = 4kT/R$ is the Johnson current noise spectral density, k is Boltzmann's constant, and T is temperature. With a typical $R \approx R_d \approx 1$ Ω at $T = 4$ K, we obtain a ~ 160 -MHz linewidth for a single junction, which is too wide for most applications.

Applications of single junction oscillators have been difficult to implement because they have low output power (10 nW), and their low (≤ 1 Ω) impedances do not match to typical high-impedance loads. In order to achieve useful power (> 0.1 mW) and impedance matching, arrays of phase-locked junctions are needed for most applications. One-dimensional (1D) [10, [11] and two-dimensional (2-D) [12]–[17] arrays of phase-locked junctions offer potential solutions to these problems. When the junctions in an array are phase-locked, arrays can provide higher output power with narrower linewidths to a matched load impedance. However, phase-locking is difficult because of the complex dynamics of these multidimensional systems.

B. Phase-Locked Arrays

Arrays of junctions have better impedance matching, higher power, and narrower linewidth than single junctions. Fig. 2 shows the geometry of a 2-D array. The array impedance depends on its width and length, M columns each with N junctions in the voltage state. The available power from a phase-locked 2-D array in the sinusoidal operating regime ($V_{dc} \geq V_c$ for each junction) is proportional to the number of phase-locked junctions, $P_A = MN I_c V_c / 8$. The length-to-width ratio can be chosen to achieve impedance matching $N/M = R_L/R$, so that the power delivered to a matched load is [12], [13]

$$P_A^L = \frac{N M I_c V_c}{8} = \frac{M^2 I_c^2 R_L}{8}. \quad (4)$$

With V_c fixed and I_c maximized (2.8 mA for Nb junctions), the total power delivered to a matched load is proportional to the square of the number of columns M . This gives 2-D arrays an additional degree of freedom over 1D arrays to increase and tune the power delivered to a fixed load. For the 1.4 THz minimum operating frequency ($V_c = 2.8$ mV), the power can be tuned to 4.9 mW by choosing $M = 10$ and $N = 500$ to match the array to a 50 Ω load. This delivered power is sufficient for both on-chip or off-chip applications, and the 5000-junction integration is achievable with present fabrication technology. Even higher power levels can be achieved by increasing the number of junctions accordingly.

For phase-locked arrays of junctions, the linewidth is reduced by the total number of phase-locked junctions [6], [13]

$$\Delta f_A = \frac{\Delta f_{JJ}}{MN}. \quad (5)$$

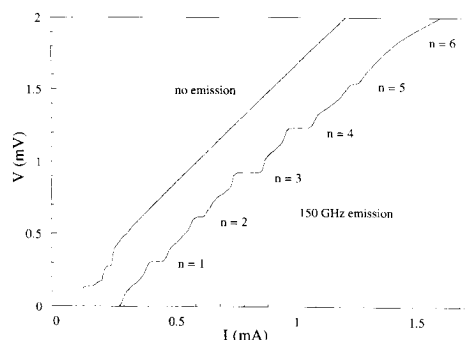


Fig. 3. Detector I - V curve displaying Shapiro steps.

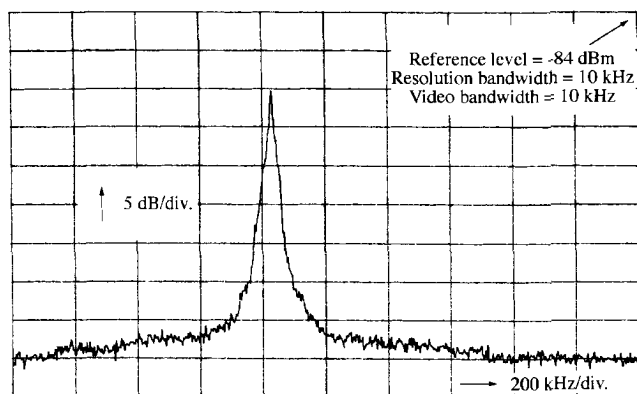


Fig. 4. Emission peak after 100 video averages at 88.844 GHz showing a ~ 13 -kHz linewidth.

Arrays with $M = 10$ and $N = 500$ would have a linewidth of ~ 33 kHz at 4 K, which is sufficiently narrow for most applications.

III. EXPERIMENTAL RESULTS

The first demonstration of complete phase locking in 2-D arrays was accomplished by using single Josephson junctions as on-chip detectors [12], [13]. Emission was coupled from a 2-D array to a detector junction through a dc-blocking capacitor. The capacitor enabled the array and the detector junction to be biased independently. When the array was biased in the voltage state, emission was coupled to the detector causing the detector's intrinsic Josephson oscillations to lock to the array's emission. This phenomenon is observed in the detector's I - V curve as flat voltage steps at voltages $V_{dc} = n\Phi_0 f$, where f is the drive frequency and $n = 0, 1, 2, \dots$ is the step number. These steps are called Shapiro steps. The number of steps and their widths depend on the amplitude of the drive.

Fig. 3 shows the detector junction I - V curve for a 10-by-10 junction 2-D array coherently emitting at 150 GHz [12], [13]. Since the $0.4\text{-}\mu\text{W}$ coupled to the detector junction at this frequency agrees with the expected theoretical power, all 100 junctions in the array are phase locked. This array showed Shapiro steps at voltage tunable frequencies ranging from 60–210 GHz, indicating broad band tunability.

More recently [15], the emission from 10×10 arrays has been coupled off-chip to room-temperature mixers through a fin-line antenna and WR-12 waveguide. A single voltage-tunable peak was detected in the frequency range from the 53-GHz cutoff frequency of the waveguide up to 230 GHz. Fig. 4 shows an example spectral peak with a linewidth of ~ 13 kHz.

These results were the first off-chip linewidth and power measurements of phase-locked 2-D arrays where a detailed comparison was made with theory. It was found that a stripline resonance in the antenna reduced the array dynamic resistance and thereby the emission linewidth (see (3)) from the ~ 2 -MHz linewidth expected for a nonresonant-coupled array. From 84–90 GHz, the linewidth varied approximately one order of magnitude.

IV. CONCLUSION

Josephson oscillators are voltage tunable with potential emission at GHz and THz frequencies. LTS 2-D arrays have demonstrated complete phase locking and narrow linewidths over broadly-tunable microwave frequencies. HTS technology is desirable for Josephson oscillators because the higher intrinsic frequencies would enable higher-frequency oscillators. The impact of HTS Josephson devices on precision frequency synthesis and measurement depends largely upon improvement of HTS thin-film fabrication technology.

REFERENCES

- [1] D. G. McDonald, V. E. Kose, K. M. Evenson, J. S. Wells, and J. D. Cupp, "Harmonic generation and submillimeter wave mixing with the Josephson effect," *Appl. Phys. Lett.*, vol. 15, pp. 121–122, Aug. 1969.
- [2] P. A. Rosenthal, E. N. Grossman, R. H. Ono, and L. R. Vale, "High temperature superconductor-normal metal-superconductor Josephson junctions with high characteristic voltages," *Appl. Phys. Lett.*, vol. 63, pp. 1984–1986, Apr. 1993.
- [3] W. C. Stewart, "Current-voltage characteristics of Josephson junctions," *Appl. Phys. Lett.*, vol. 12, pp. 277–280, Apr. 1968.
- [4] D. E. McCumber, "Effect of ac impedance on dc voltage-current characteristics of superconducting weak-link junctions," *J. Appl. Phys.*, vol. 39, pp. 3113–3118, June 1968.
- [5] K. Yoshida and F. Irie, "Frequency conversion in a long Josephson junction with a moving vortex array," *Appl. Phys. Lett.*, vol. 27, pp. 469–470, Oct. 1975.
- [6] A. K. Jain, K. K. Likharev, J. E. Lukens, and J. E. Sauvageau, "Mutual phase-locking in Josephson junction arrays," *Phys. Rep.*, vol. 109, pp. 309–426, 1984.
- [7] R. P. Robertazzi and R. A. Buhrman, "Josephson terahertz local oscillator," *IEEE Trans. Magn.*, vol. 25, pp. 1384–1387, Mar. 1989.
- [8] A. I. Larkin and Yu. N. Ovchinnikov, "Radiation line width in the Josephson effect," *Sov. Phys. JETP*, vol. 26, pp. 1219–1221, June 1968.
- [9] M. J. Stephen, "Noise in the ac Josephson effect," *Phys. Rev.*, vol. 182, pp. 531–538, June 1969.
- [10] B. Bi, S. Han, and J. E. Lukens, "Radiation linewidth of phase-locked distributed array in the submillimeter wave range," *Appl. Phys. Lett.*, vol. 62, pp. 2745–2747, May 1993.
- [11] S. Han, B. Bi, W. Zhang, and J. E. Lukens, "Demonstration of Josephson effect submillimeter wave sources with increased power," *Appl. Phys. Lett.*, vol. 64, pp. 1424–1426, Mar. 1994.
- [12] S. P. Benz and C. J. Burroughs, "Coherent emission from two-dimensional Josephson junction arrays," *Appl. Phys. Lett.*, vol. 58, pp. 2162–2164, Apr. 1991.
- [13] ———, "Two-dimensional arrays of Josephson junctions as voltage-tunable oscillators," in *Proc. Third Int. Superconductive Electron. Conf.*, Glasgow, June 1991, pp. 230–237, *Supercon Sci. Technol.*, vol. 4, pp. 561–567, 1991.
- [14] P. A. A. Booi, S. P. Benz, T. Doderer, D. Hoffmann, J. Schmidt, S. Lachenmann, and R. P. Huebener, "Frequency dependence of the emission from 2D array Josephson oscillators," *IEEE Trans. Appl. Supercon.*, vol. 3, pp. 2493–2495, Mar. 1993.
- [15] P. A. A. Booi and S. P. Benz, "Emission linewidth measurements of two-dimensional array Josephson oscillators," *Appl. Phys. Lett.*, vol. 64, pp. 2163–2165, Apr. 1994.
- [16] K. Wiesenfeld, S. P. Benz, and P. A. A. Booi, "Phase-locked oscillator optimization for arrays of Josephson junctions," *J. Appl. Phys.*, vol. 76, pp. 3835–3846, Sept. 1994.
- [17] P. A. A. Booi and S. P. Benz, "Resonances in two-dimensional array oscillator circuits," *IEEE Trans. Appl. Superconduc.*, vol. 5, pp. 2899–2902, June 1995.