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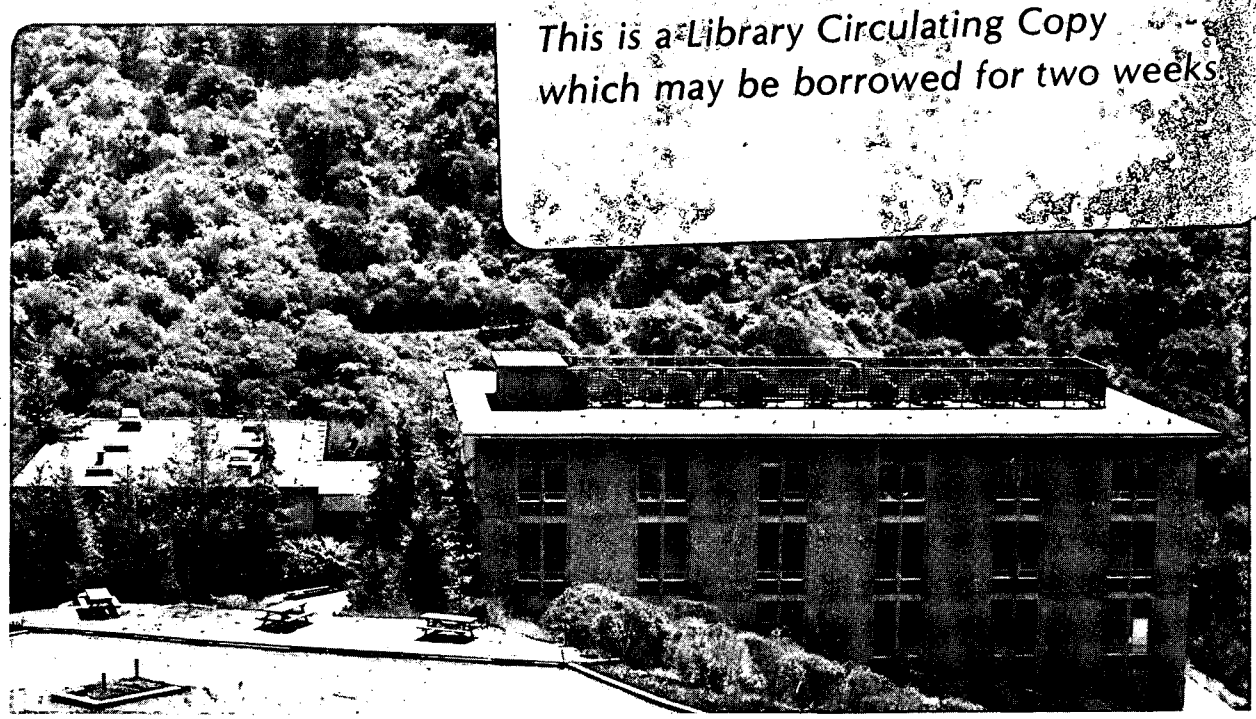

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PERIOD THREE GENERATION ON MICROWAVE-INDUCED CONSTANT-VOLTAGE STEPS OF JOSEPHSON TUNNEL JUNCTIONS

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Abstract

We report the observation of one-third harmonic generation in small Josephson tunnel junctions driven with a microwave signal in the frequency range 8 to 18 GHz. This phenomenon was observed both with the junction biased in the zero voltage state and on microwave-induced constant-voltage steps in the current-voltage characteristic. With high levels of applied microwave power the period-tripled signal was detected on steps up to order 120.

Introduction

Over the past six years, there have been extensive digital and analog computer simulations of subharmonic generation and chaotic behavior in microwave-driven Josephson tunnel junctions.[1] Most of these simulations were for zero average voltage. Although there have been relatively few experimental investigations[2] of these phenomena, we recently reported[3] the experimental observation of one-third harmonic generation at zero voltage and current; the results were in reasonable agreement with computer simulations. In this paper we summarize these findings, and present new results for period-tripling in junctions biased on microwave-induced steps at nonzero voltages.

Theoretical Model

According to the resistively shunted junction model (insert Fig. 2) the equation of motion for the phase difference ϕ across a junction biased with both static and microwave currents is

$$\frac{\hbar C}{2e}\frac{d^2\phi}{dt^2} + \frac{\hbar}{2eR}\frac{d\phi}{dt} + I_o\sin\phi = I + I_m\sin\omega_m t + I_n(t). \quad (1)$$

Here, I_o is the critical current of the junction, C is the shunt capacitance, R is the shunt resistance, and I, I_m and I_n are the static bias current, the microwave current at frequency ω_m, and the noise current, respectively. This equation contains no spatial dependence of ϕ and therefore models a Josephson junction with dimensions smaller than the Josephson penetration depth. In normalized form Eq. (1) may be written as

$$d^2\phi/d\tau^2 + \alpha_o d\phi/d\tau + \sin\phi = \rho + \rho_m\sin\Omega\tau + \rho_n(\tau). \quad (2)$$

Here, $\tau = \omega_{po}t$ is the time normalized to the inverse of the maximum plasma frequency, $\omega_{po} = (2eI_o/\hbar C)^{1/2}$, $\alpha_o = 1/Q_o = 1/\omega_{po}RC$ is the damping parameter, $\Omega = \omega_m/\omega_{po}$ is the normalized microwave frequency and ρ, ρ_m and ρ_n are the static bias current, microwave current and noise current normalized to I_o.

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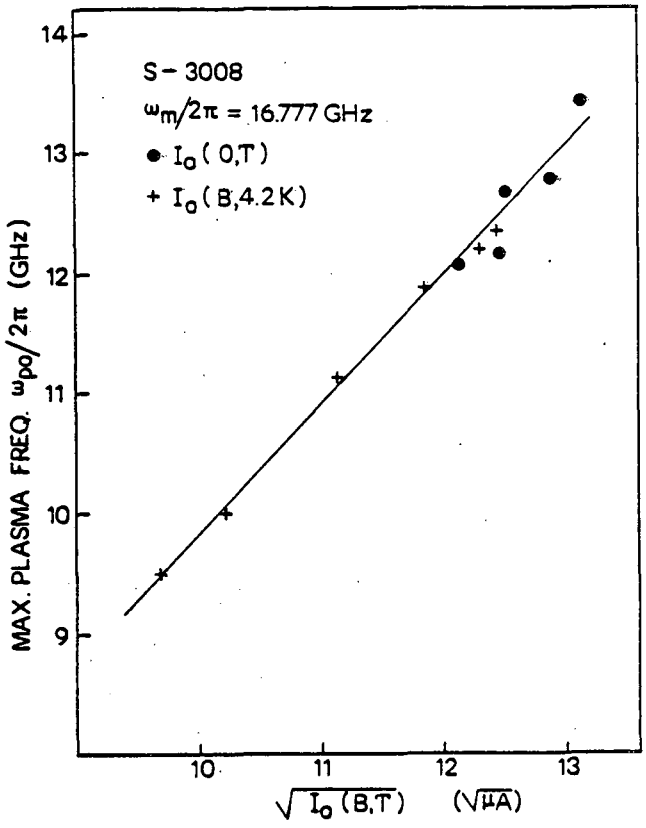

Figure 1. Maximum plasma frequency $\omega_{po}(B)/2\pi$ measured in half-harmonic excitation experiments with applied B-field versus the square root of the suppressed critical current for $0 \leq B \leq 4.0$ gauss. Also plotted is $\omega_{po}(0)$ found similarly in the temperature range $3.0\ K \leq T \leq 4.8\ K$ versus $\sqrt{I_o(0,T)}$. (Junction S-3008)

Equation (2) also models a periodically driven damped pendulum. For zero current bias and in the zero voltage state computer simulations based on this equation show the existence of bands of even- and odd-subharmonic solutions in the microwave frequency-amplitude plane, often separated by regions of chaos.[4]

Experimental Results

We made measurements on 4 underdamped Nb-NbO_x-Pb overlap Josephson tunnel junctions approximately 30 × 30 μm^2 in area and with a critical current density in the range 10 to 70 A cm^{-2}. The corresponding Josephson penetration depth varied from about 100 μm to 35 μm. Thus, we could neglect any spatial dependence of ϕ in junctions with the lower critical currents but not necessarily in those with the higher values. The experimental apparatus and measurement techniques were identical to those reported earlier,[3] and included detailed in situ measurements of the parameters I_o, ρ_n, ω_{po} (i.e. C), Q_o (i.e. R) and ρ_m. We could also adjust the maximum plasma frequency ω_{po} by applying a magnetic field B in the plane of the

junction to reduce the critical current $I_o(B,T)$ at a given temperature T. The plasma frequency was measured using half-harmonic excitation,[5] and is plotted vs. $I_o^{1/2}(B,T)$ in Fig. 1. For this junction, the data yield a value of C = 80 pF from the prediction $\omega_{po} = [2eI_o(B,T)/\hbar C]^{1/2}$.

We observed one-third harmonic generation for three different cases:

(1) For B = 0, ρ = 0 and V = 0, that is, for the junction biased in the zero voltage state. Both narrow-band signals (see Fig. 2) and relatively broad-band noisy (intermittent) signals were observed. In this regime the phase ϕ oscillates about zero with $\langle\dot{\phi}\rangle$ = 0.

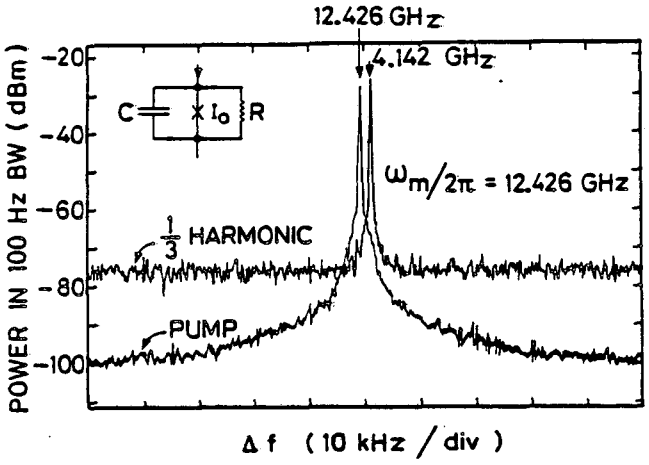

Figure 2. Typical spectrum analyzer display showing the one-third harmonic generation in a Josephson junction (S-6/7-4) biased in the zero voltage state. For comparison of the linewidths the stored display of the microwave pump signal at 12.426 GHz and the one-third harmonic signal emitted by the junction are shown on the same frequency span. The resolution bandwidth is 100 Hz and the experimental parameters are: I_o = 163 μA, $\omega_{po}/2\pi$ = 14.45 GHz (Ω = 0.86), and ρ_m = 1.28. The insert shows the resistively shunted junction model.

(2) For B = 0, ρ = 0 and V = $(1/3)\hbar\omega_m/2e$, that is, with the junction biased on the microwave-induced subharmonic step. An example is illustrated in Fig. 3. In this regime ϕ advances with time.

(3) For B = 0, ρ = 0 and V = $n\hbar\omega_m/2e$, where n is an integer, that is, when the junction is biased on an integer-valued microwave-induced step. Typical results are shown in Fig. 4. This generation was observed at 13.28 GHz for values of n up to 120, corresponding to a voltage of about 3.3 mV. This voltage was slightly above $(\Delta_{Nb} + \Delta_{Pb})/e$ = 2.8 mV, where Δ_{Nb} and Δ_{Pb} are the measured energy gaps of niobium and lead. In this regime, ϕ advances with time. These results were obtained only in the junction (S-5001) with the higher critical current (585 μA), for which there may have been a significant spatial nonuniformity of the phase difference, and in the presence of a magnetic field. The amplitude of the 1/3 harmonic signal was very sensitive to the values of B, ρ_m, and ρ. With B = 4 gauss, $\omega_{po}/2\pi$ = 23.2 GHz, α = 0.05 and T_{bath} = 4.2 K, two representative points at which we observed 1/3 harmonic generation were (Ω,ρ_m) = (2.1,100) and (2.3,82). The fact that one can observe period 3 generation on integer-valued microwave induced steps appears not to have been predicted in any simulation for a spatially uniform phase difference and B = 0.

The state diagram plotted in Fig. 5 summarizes the results of our experiments and digital simulations for one-third harmonic generation at V = 0. In studying the experimental results, one should bear in mind that the 1/3 harmonic signal could be observed only at

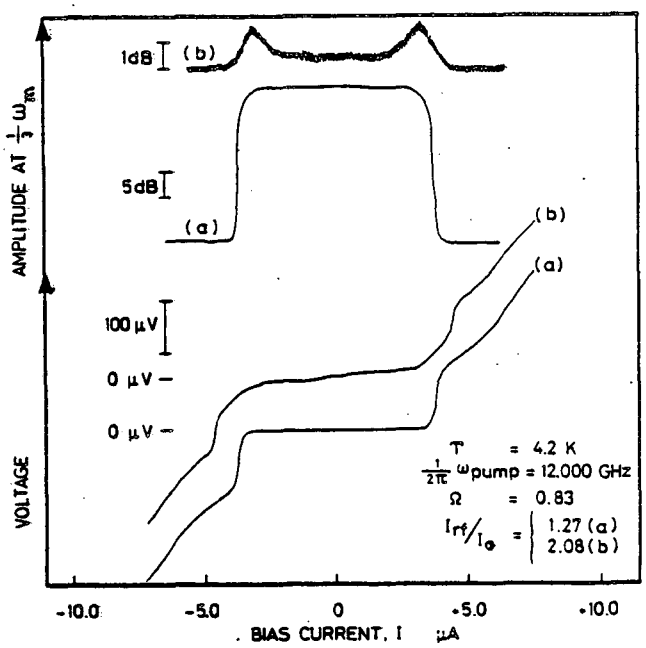

Figure 3. Amplitude of the detected one-third harmonic signal (upper trace) and static voltage (lower trace) as functions of the current bias at two different levels of pump power. (a) XYY recording with one-third harmonic in the zero voltage state. (b) XYY recording for a weak one-third harmonic signal on one-third harmonic steps (barely visible in the I-V characteristic).

discrete frequencies for which there was good coupling between the junction and the detector. Thus, the discrete points almost certainly represent a broad region over which the subharmonic generation occurs. In the same way, the simulations represent a continuous range of drive frequency and amplitude over which one-third harmonic signal is generated. Given the uncertainties in the determination of the experimental parameters, particularly the magnitude of the microwave current, the agreement between the experimental and simulated values is quite reasonable.

We are continuing these experiments to search for higher order subharmonics and to study routes to chaos. We are also carrying out computer simulations in order to understand the one-third harmonic generation on the microwave-induced steps.

Acknowledgments

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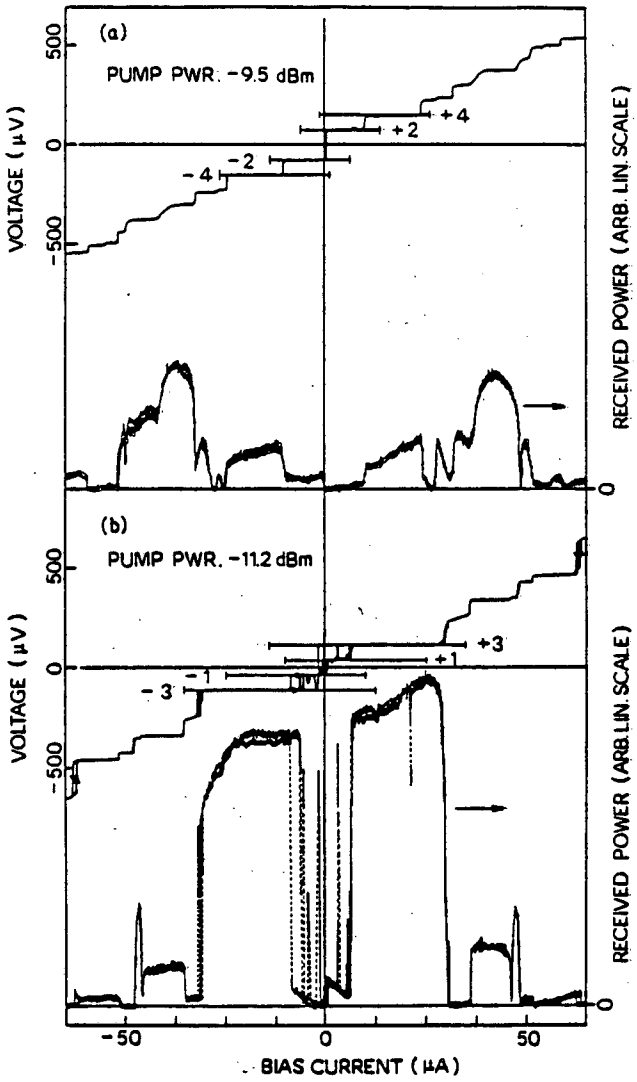

Figure 4. Typical XYY recording of the bias current dependence of the voltage (upper trace) and the corresponding detected one-third harmonic power (lower trace) generated on (a) even and (b) odd numbered microwave-induced steps for junction S-5001 at 4.2 K. The detected frequency was 6.122 GHz, the resolution bandwidth was 10 kHz, the microwave frequency $\omega_m/2\pi$ was 18.366 GHz, and the plasma frequency $\omega_{po}(0)/2\pi$ was 23.2 GHz. The plasma frequency was tuned by means of a magnetic field (see text) to produce reduced microwave frequencies of (a) $\Omega = 2.3$ and (b) $\Omega = 2.1$.

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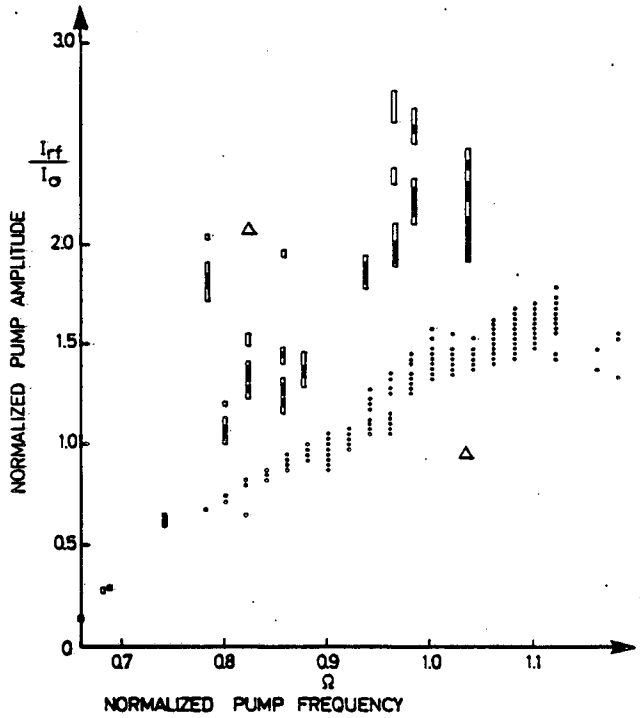

Figure 5. Normalized microwave pump amplitude ρ_m vs. normalized pump frequency Ω showing regions for which one-third harmonic signal occurs. The results of numerical simulations are also shown.
Experiment. Junction S-6/7-4 with B = 0: ■ narrow band 1/3-harmonic and □ broadband noisy or intermittent 1/3-harmonic at V = 0, ρ = 0 (case 1); △ 1/3-harmonic at $V = (1/3)\hbar\omega_m/2e$ (case 2). Parameters: I_o = 163 μA, $\omega_{po}/2\pi$ = 14.45 GHz, α = 0.05 and T_{bath} = 4.2 K.
Simulations. • narrow band 1/3-harmonic at V = 0, α = 0.05.

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