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HARMONIC MIXING OF MICROWAVE AND FAR-INFRARED LASER RADIATION USING A JOSEPHSON JUNCTION

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Simultaneous irradiation of a Josephson junction with ≈ 10 GHz microwave power and 891-GHz laser radiation produces a 60-MHz beat between the fundamental laser frequency and harmonics of the klystron, ranging from the 84th to the 100th as the klystron is tuned. Observation of such high-order harmonic mixing of klystron and laser signals is unprecedented.

Harmonic generation from a microwave source has important applications both for accurate frequency measurements in the infrared and for heterodyne signal detection via harmonic mixing. The emphasis here is on the very active field of infrared frequency measurements,[1] but the heterodyne detection problem is closely related. Recent work on frequency synthesis into the infrared[2] uses reference klystrons in the range 35–75 GHz. For the most accurate measurements the reference frequency must be a primary frequency standard, i.e., a cesium beam device at ≈ 9 GHz. Our work is motivated in part by this consideration.[3]

The first and only other report on harmonic mix-

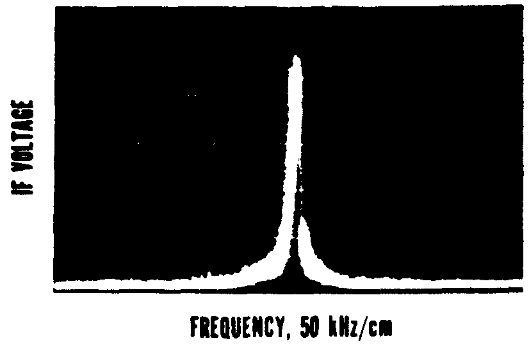

FIG. 1. Spectral line representing the beat between the 84th harmonic of 10.6 GHz and the HCN laser emission at 891 GHz. This figure is from a 1-min exposure with 60 sweeps per second of the analyzer with a 6-dB noise bandwidth of 8 kHz.

ing in Josephson junctions is by Grimes and Shapiro[4] who experimented with third-order harmonic mixing between signals at 24 and 72 GHz.

Our apparatus consisted of an adjustable Nb-Nb point-contact junction biased from a constant current source and immersed in superfluid He at 2.0 K. It was irradiated with x-band and ir power through polyethylene windows near the bottom of the Dewar. The i.f. signal from the junction went first to a 60-MHz amplifier (10-MHz bandwidth, 1.5-dB noise figure) and then to a spectrum analyzer.

Figure 1 illustrates a typical signal as observed on the spectrum analyzer for the beat between the 84th harmonic of 10.60358 GHz and the fundamental HCN laser output at 890.761 GHz. All of the detailed results in this report are for this order of harmonic mixing. Not all junction adjustments produce beat signals but if the first current step of the laser at 1.84 mV is observable[5] then the beat will appear if the 10-GHz power is properly adjusted. Useful critical currents ranged from 5 μA to 1 mA. The maximum amplitude for the signal from a typical junction (referred to the junction) was 12 μV rms.[6] If the laser or klystron frequencies were shifted slightly, then to an accuracy of 10%, the beat frequency shifted exactly with the laser and 84 times as much as the klystron.

From a junction biased to a voltage V_0, the predicted Josephson current with applied signals at angular frequencies ω_1 and ω_2 is[4]

$$\frac{i}{i_c} = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_k\left(\frac{2ev_1}{\hbar\omega_1}\right) J_l\left(\frac{2ev_2}{\hbar\omega_2}\right) \times \sin[(\omega_J + k\omega_1 + l\omega_2)t + \theta_{kl}], \qquad (1)$$

where v_1 and v_2 are the applied rf voltage amplitudes, i_c is the critical current, and $\omega_J = 2eV_0/\hbar$ is the Josephson frequency. $J_l(x)$ is an integer-order Bessel function. The simplest case for harmonic mixing is with zero bias, i.e., $\omega_J = 0$, in which case the current amplitude at the beat frequency $\pm\,\omega_b \equiv \omega_1 - n\omega_2$ is

$$i(\omega_b) \propto J_1(2ev_1/\hbar\omega_1) J_n(2ev_2/\hbar\omega_2). \qquad (2)$$

As is well known,[7] a change in the supercurrent at zero voltage bias shifts the resistive part of the dc I-V curve in synchronism with the supercurrent. Therefore, the beat frequency supercurrent can be observed by biasing at a fixed current greater than the zero voltage current. This bias condition, however, contradicts our assumption of zero voltage so we must now consider the finite voltage case.

As can be seen by inspection of Eq. (1), there are many bias voltages which will result in a response at ω_b with various values of n. All of these involve combinations of ω_J with ω_1 and ω_2 and consequently have the voltage-frequency dependence of ω_J. In our experiments the observed signal does not shift in frequency as V_0 is changed. This is conclusive proof that ω_J is not involved directly in the response we observe. The absence of beats dependent on ω_J can be understood from a theory of the Josephson linewidth discussed by Silver, Zimmerman, and Kamper.[8] In the present case the linewidth for self-oscillation is determined by the normal resistance of the junction and is estimated to be 290 MHz, which is much broader than the $\approx$ 15-kHz width of the beat of Fig. 1. The $\approx 10^4$ times greater width makes these signals unobservable under our conditions. The narrow beat results only because the Josephson self-oscillation is not involved.[9]

The microwave power dependence of the beat signal for a junction with a critical current of 700 μA and sufficient laser power to produce a 150-μA current step at 1.84 mV is illustrated in

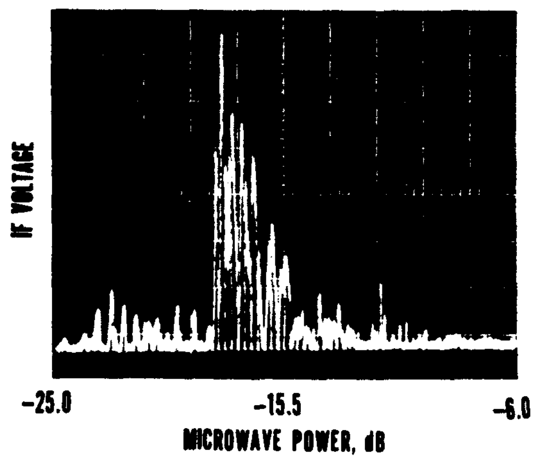

FIG. 2. Microwave power dependence of the beat signal. 0 dB is roughly 20 mW of power flux on the junction.

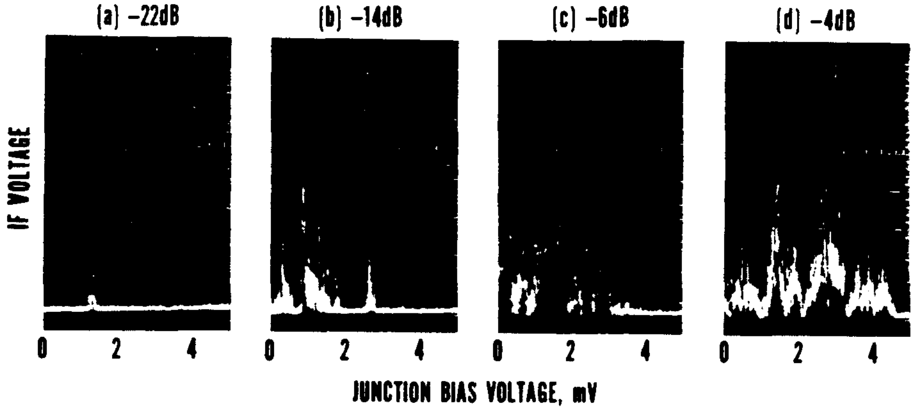

FIG. 3. Beat signal dependence on bias voltage for four different microwave power levels.

Fig. 2. For these data the junction was biased at zero current. Biases with nonzero currents or voltages produce similar patterns with about the same amplitudes until levels of a few millivolts are reached where the beat disappears into the noise. The shape of the envelope of the oscillatory behavior as a function of microwave power is variable from junction to junction, sometimes having a rather discontinuous rise as shown here to the left of center and sometimes having a more nearly Bessel-function-like response. A qualitatively different power dependence is occasionally observed, showing two superimposed oscillatory patterns, one oscillating several times faster than the other as a function of power. In all cases the beat amplitude decreases with increasing x-band power much faster than predicted by Eq. (2).

For the same junction and laser power level as used for the power dependence of Fig. 2 we have studied the bias voltage dependence of the beat signal and that is shown in Fig. 3. The first point of interest is to note the large amount of fine structure that appears as a function of voltage. On close examination it was found that the periodicity in voltage of this structure was the same as the periodicity for the x-band current steps, i.e., 22 μV for this applied frequency. This is consistent with the results of Grimes and Shapiro[4] with much lower-order harmonic mixing and is presumably related to the variation in impedance of the junction as current steps are crossed. Note further in Fig. 3(a) that, even for power levels just large enough for the beat to be observed, the voltage dependence already has a well-defined fine structure. The beat's first appearance at about 1.2 mV may be related to the proximity of the "knee" of the I-V curve[7] at 1 mV but that seems unlikely since the knee disappears under the conditions of irradiation that produce the beat. In Fig. 3(b) a third bias region for the beat has appeared near the energy gap voltage of 2.8 mV.

In summary then, we have demonstrated high-order harmonic mixing with a Josephson junction, but the response does not follow the prediction of the simple voltage-biased model. In fact, about the only qualitative result from Eq. (1) that is actually observed is the oscillatory response as a function of applied microwave power level. An adequate model would probably have to include the detailed shape of the I-V curve and the fact that the junction is biased from a constant current source. Since a study[5] of the dc current steps has indicated a Josephson response up to 8 THz, it is expected that these harmonic mixing experiments can be considerably extended.

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[1]For a review see: H.S. Boyne, Proceedings of the 24th Annual Symposium on Frequency Control (Electronic Industries Assoc., Washington, D.C., 1970), p. 233.

[2]Probably the best previous result on harmonic generation into the infrared beginning with a klystron is Hocker, Rao, and Javan [Phys. Letters 24A, 690 (1967)] who obtained the 23rd harmonic of 70 GHz in a W-Si diode. It is difficult to compare this with our results since we begin at a seven times lower frequency.

[3]The x-band approach was advocated by Donald Halford.

[4]C.C. Grimes and Sidney Shapiro, Phys. Rev. 169, 397 (1968).

[5]D.G. McDonald, V.E. Kose, K.M. Evenson, J.S. Wells, and J.D. Cupp. Appl. Phys. Letters 15, 121 (1969).

[6]To calibrate the system, transmission line effects and amplifier gains must be considered. This was done by assuming the effective junction resistance was equal to the resistance defined by the I-V curve under the irradiation conditions which produced the beat. A typical resistance was 3.6 Ω. By replacing the junction with this value of resistance and using a calibrated 60-MHz source to produce the same response as a beat on the spectrum analyzer, the desired result was obtained.

[7]See Fig. 7. of Ref. 4.

[8]A.H. Silver, J.E. Zimmerman, and R.A. Kamper, Appl. Phys. Letters 11, 209 (1967). Correct Eq. (4) by replacing 8 by 4π.

[9]One small question remains. If the self-oscillation linewidth is so great as to make beats with ω_J unobservable, then why are the current steps observed since ω_J is required for them also? The answer is that if ω_J is observed through its zero frequency beat with another signal, as it is with the current steps, its linewidth is narrowed by phase locking with the applied signal. See M.J. Stephen, Phys. Rev. 186, 393 (1969).