Simulation and Measurement of HTS Josephson Heterodyne Oscillator

John Cameron Macfarlane, J. Du, R. Taylor, and C. M. Pegrum

***Abstract*—We report continuing investigations into practical applications of the ac Josephson effect as the basis for a voltage-tunable radio-frequency oscillator. We have previously demonstrated experimentally that useful power levels (10 s of nW) and linewidths of a few kHz can be achieved in the heterodyne output from a High-Temperature-Superconducting Resistive SQUID (HTS-RSQUID) operating in the frequency range 1–50 MHz. Those results were achieved with 2-junction R-SQUIDs incorporating current-biased shunt resistors of a few micro-ohms. We have now modified the fabrication procedures, and adjusted the shunt resistors and bias current values so that higher frequencies can be achieved. The Josephson junctions are of step-edge type, rather than the bi-crystal type used in our earlier work. The step-edge technique permits much more flexibility in the geometrical lay-out and utilizes the more cost-effective single-crystal MgO substrates. In the present paper, we report numerical simulations and experimental measurements on these devices in the frequency range up to 2 GHz.**

***Index Terms*—Heterodyne oscillator, high-temperature-superconducting, Josephson junction.**

I. Introduction

PRACTICAL applications of the ac Josephson effect for the generation of useful radio-frequency oscillator outputs in the MHz to GHz range have been difficult to realize, partly because the applied voltages are required to be inconveniently small (<1 microvolt), but primarily because intrinsic junction noise contributes to linewidth broadening of the emitted radiation. Typically, Johnson noise at temperatures of 50 K in the junction resistance of order 10 ohms can lead to linewidths of 500 MHz or more, which is unacceptable in most applications that might be envisaged.

We shall instead exploit the intrinsic non-linearity of Josephson devices to generate heterodyne signals in the MHz to GHz range from two oscillating junctions connected in the resistive-SQUID configuration [1]. This device consists of two Josephson junctions J1, J2 connected in series in an otherwise superconducting loop containing a small resistor R_s (see Fig. 1). A sketch of the thin-film geometry is also shown in Fig. 1.

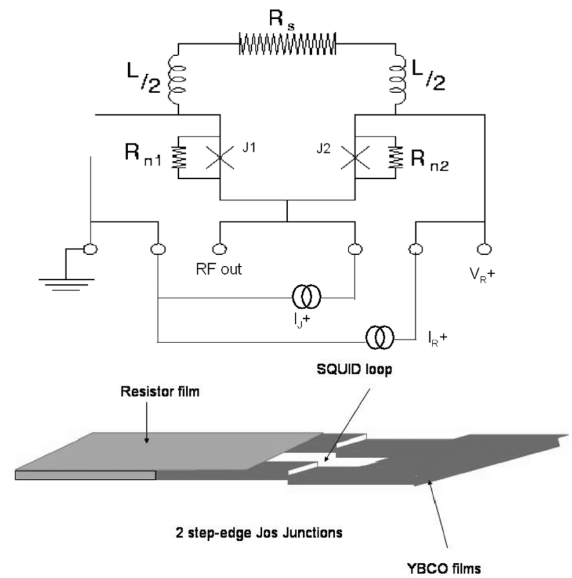

Fig. 1. (Upper), schematic circuit of R-SQUID device; components are explained in the Text; (lower:), sketch of thin-film layout used to produce the R-SQUID.

The resistors R_{n1}, R_{n2} represent the normal resistance of the step-edge junctions, typically 2–10 ohms. The inductors L/2 represent unavoidable inductances in the device structure, and are estimated to be in the range 10–20 pH. Currents Ij, Ir are supplied from dc sources, and the heterodyne rf output is extracted via a dc blocking capacitor from the indicated terminal to a co-axial cable. With this arrangement, the separate junctions are voltage-biased and typically oscillate at 10–100 GHz, while the heterodyne output can be precisely controlled by adjustment of I_r in the 100 MHz to 2 GHz range, with an intrinsic linewidth determined by Johnson noise in R_s:

$$\Delta f = 4\pi k T R_s/\phi_0^2 \tag{1}$$

where k is Boltzmann's constant, and the flux quantum $\phi_0 = 2 \times 10^{-15}$ Wb.

Before experimental work was started, we carried out numerical simulations of the devices' performance, using JSIM and JSPICE3 circuit analysis software packages, primarily to look at the behavior in the time domain. An example of the output obtained from this modeling is shown in Fig. 2. The step-edge junctions were modeled as Resistively-Shunted-Junctions. More extensive modeling results are presented in greater detail in a companion paper at this Conference [2].

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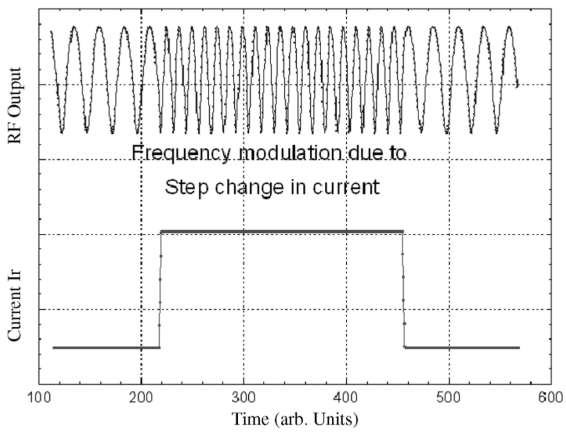

Fig. 2. Example of time-domain simulation of an R-SQUID, obtained by JSIM. The response of the heterodyne frequency to a step change in the current Ir is illustrated.

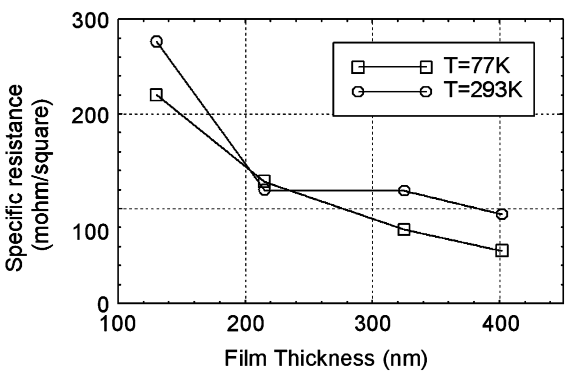

Fig. 3. Measurements of the Au-film specific resistance as a function of thickness, at 77 K and at room temperature.

II. Experimental Approach

Earlier work [3] used resistors R_s with values around 20 micro-ohms, with which Δf is expected to be of the order 17 kHz at $T = 20$ K. Heterodyne frequencies obtained at that time were in the range 1–50 MHz, with bias currents in the range 0–5 mA. In the present phase of this project, the frequency of interest is extended to $\sim$2 GHz. To meet this requirement, either (i) the resistor R_s has to be increased by about a factor of 100 into the milli-ohm range; or (ii) bias currents I_r have to be increased by a similar factor. In practice, we used Au-film resistors of order 1–10 milli-ohm, and bias currents in the range 0.2–1 mA, giving a theoretical range of heterodyne frequencies of 0.2–10 GHz.

A. Resistors

Before the micro-lithographic masks were designed, it was necessary to obtain a realistic value for the specific resistance of our Au films, so that the desired resistor values of 1–10 mohms could be achieved. Four samples of Au film resistors were prepared with different film thicknesses (100 nm–400 nm), and the specific resistance values measured at room temperature and liquid N2 temperature (77 K) (Fig. 3). To avoid large contact resistances, however, it was essential to deposit *in-situ* a layer of Au on top of the newly-deposited YBCO [4].

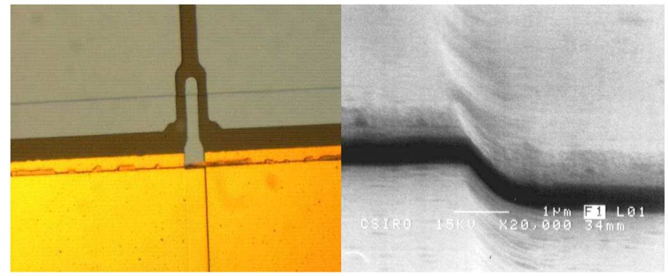

Fig. 4. A photograph of a fabricated device junction area (left) and an SEM micrograph of the YBCO step-edge junction (right). The step, produced on the MgO substrate by Ar-ion beam etching, is $\sim$400 nm in height. The magnification is $\times$20,000.

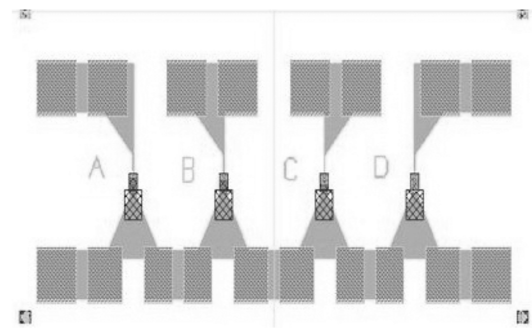

Fig. 5. Sketch of the 4-device layout on a 5 mm $\times$ 10 mm chip. Hatched rectangles represent the Au-film resistors.

B. Junctions

The devices are based on the established step-edge YBCO junction technology developed at CSIRO [5], [6]. The MgO substrates were first etched by Ar-ion beam to produce steps of $\sim$400 nm high in the desired positions. The 200–220 nm thick YBCO films, and 50 nm *in-situ* Au films, were then deposited by Theva GmbH [7]. The 10 mm $\times$ 10 mm substrates were then returned to CSIRO, where eight devices of variable designs were fabricated on each one. A photograph of a fabricated device junction area and an SEM micrograph of a typical step-edge junction are shown in Fig. 4. The devices are highly reproducible, on-chip and from chip to chip, as evidenced by critical-current and resistor measurements [5], [6].

The finished substrate was diced into two 5 mm $\times$ 10 mm chips (Fig. 5) for packaging and measurements. The simultaneous fabrication of multiple devices enabled the variability of some important device parameters, such as R_s, I_c and R_n, to be assessed at an early stage of device development.

III. Experimental Results and Discussion

Initial tests were done while cooling the device in the gas space of a liquid-helium Dewar, so that a wide range of operating temperatures could be readily achieved. Temperatures were recorded with a calibrated Si diode mounted on the chip holder. With a temperature in the range 20 K–60 K, a dc current Ij is applied until the critical current has been reached, typically 200 μa to 800 μa for 2 junctions in parallel.

The onset of heterodyne oscillation in the range 0.2–2 GHz can then be observed during fine adjustment of Ij, with the aid of

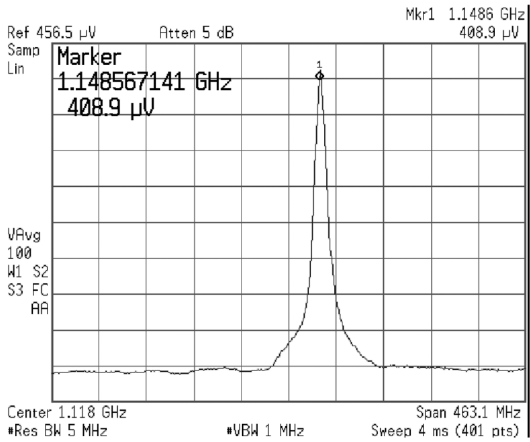

Fig. 6. Spectrum analyser trace obtained by suitable adjustment of the bias current Ij. A low-noise broadband rf pre-amplifier (gain 20 dB) was used.

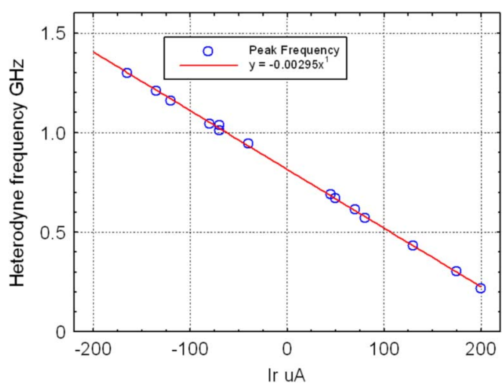

Fig. 7. Dependence of heterodyne frequency on current Ir applied to the resistor R_s.at $T = 27$ K. Negative slope is due to arbitrary choice of polarity of current connections.

a spectrum analyser. When a peak is located, (see Fig. 6) its amplitude is optimized by fine adjustment of Ij. Then by applying current I_r to the resistor R_s, the frequency can be adjusted. The range of frequency explored here, but by no means set by these limits, is 0.2–1.5 GHz, as illustrated in Fig. 7. The amplitude of the heterodyne oscillation depends on the optimum magnitude of the bias current, which is closely related to the junction critical current, which in turn is temperature dependent. The close correspondence between the temperature dependence of the junction bias current and that of the oscillation amplitude is demonstrated in Fig. 8. The exact value of R_s is given by the slope $\Delta f/\Delta I_r$. of the line in Fig. 7, and in this case was found to be 6.095 mohms at 27 K, confirming that the mask design for the resistors was soundly based on preliminary measurements (Fig. 3) of the specific resistance of the unstructured Au films. The upper limit on heterodyne frequency is a subject of on-going work, but is expected to be at least 10 GHz. It will ultimately be limited by parasitic effects, e.g., inductance of interconnects etc.

A. Heterodyne Oscillation Linewidth

The linewidth is fundamentally determined by Johnson noise in R_s, according to (1). For example, thermally-induced voltage noise in a 6 mohm resistance corresponds to a linewidth of order

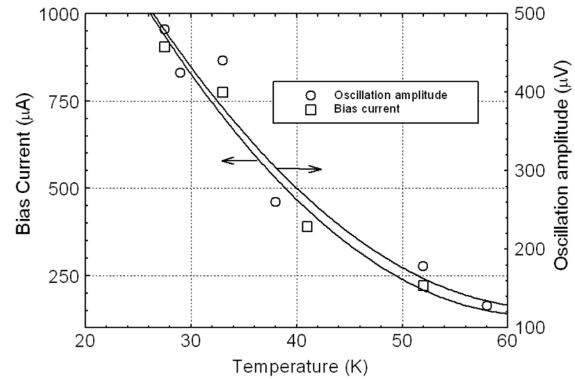

Fig. 8. The junction optimum bias currents (open squares, left axis) and the heterodyne oscillation amplitudes (open circles, right axis) have similar temperature dependences. The solid lines are best quadratic fits to the two data sets.

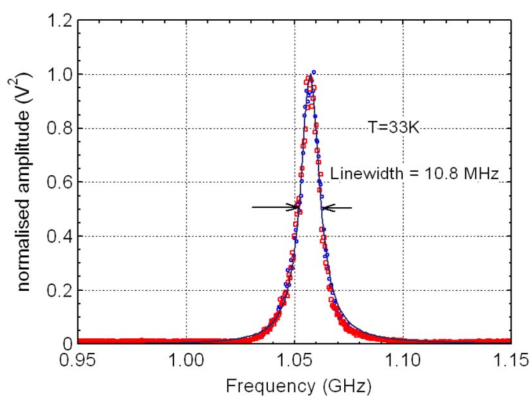

Fig. 9. Example of heterodyne oscillation linewidth measurement. The oscillation amplitude was squared and peak normalized to 1.

8 MHz at 33 K, whereas linewidths observed in our present work are around 10 MHz, Fig. 9. A possible cause of excess linewidth broadening is the fact that HTS junctions universally have been shown to have excess voltage noise due to critical-current fluctuations [8], which translates to frequency "jitter" via the ac Josephson effect. This source of noise is generally ascribed to the trapping-de-trapping of Cooper pairs at sites within the grain-boundary junction, and as such, is largely independent of the fabrication technique. It is noteworthy that R-SQUIDs made from low-temperature-superconducting thin films, e.g. Niobium, in which the tunnel barrier is relatively free of such defects, show greatly reduced, even negligible, linewidth broadening, and for this reason, have been serious contenders for the realization of an absolute noise thermometer [9].

Another possible source of additional linewidth broadening may be external magnetic field noise or current noise in bias supplies, both of which can phase-modulate the heterodyne signal [10]. A frequency dependence of the linewidth is not expected, because according to (1), the ratio $\Delta f/T$ should be independent of frequency and of temperature, for a given value of R_s. Nevertheless, over the frequency range covered in this paper (0.2 GHz–1.5 GHz), and temperatures between 27 K–58 K, a weak frequency dependence was observed, as shown in Fig. 10. This may be explained by the fact that we have not allowed for a possible frequency- or temperature-dependence of R_s. A more detailed evaluation of the noise temperature and linewidth broad-

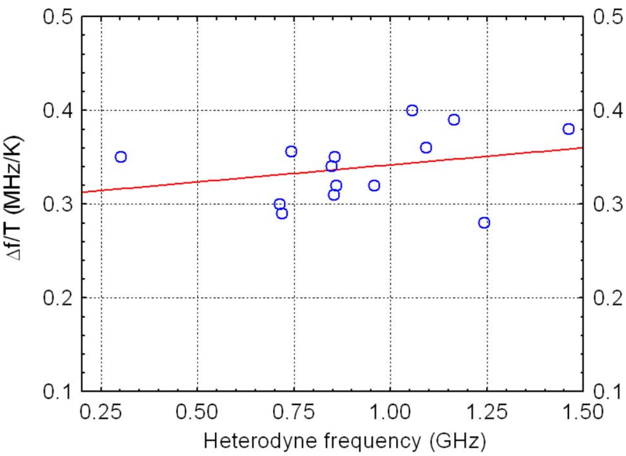

Fig. 10. The linewidth/temperature ratio showed a weak dependence on the heterodyne frequency.

ening in HTS R-SQUIDs has been recently published [12], and following on from that work, a thorough investigation of all linewidth broadening mechanisms will be carried out.

It is interesting at this point to refer to an alternative type of superconducting Josephson-effect oscillator which has been thoroughly investigated in recent years: the Josephson Flux-Flow Oscillator (FFO) [11]. Operating at frequencies of 500 GHz–700 GHz, free-running linewidths around 10 MHz have been reported. Additional sources of noise were partly attributed to resonances or other spurious effects associated with the relatively complicated tuning arrangement, which required the application of a variable magnetic field. Those helium-temperature FFO devices have not however, to our knowledge, been realized in HTS materials.

IV. Conclusion

The design, modeling, fabrication and experimental demonstration of Josephson heterodyne oscillators providing useful rf outputs at frequencies up to 1.5 GHz and temperatures up to 58 K have been carried out. Predictions of JSIM models have been verified, and new directions for further research, primarily into the causes of linewidth broadening, have been indicated.

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