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Experimental investigation of a high frequency sampling system based on shunted Josephson junctions

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Abstract. We propose a new type of sampler design based on shunted junctions ($\beta_c = 1$). The sampler is to be used for the investigation of single flux quantum devices (RSFQ) employing similar junctions (Kaplunenko *et al* 1989, Filippenko *et al* 1991). We measure the time resolution of the sampler and delay time of the shunted Josephson junction array. The circuit was manufactured on a single chip and was DC powered. We employed Nb–AlO$_x$–Nb tunnel junctions of 300 A m^{-2} critical current density and observed Josephson oscillations of the output junction at frequencies from 6 to 50 GHz. Despite a long plasma period of 20 ps the time resolution was 5 ps. The transmission line of 27 Josephson junctions (critical current 165 μA each) demonstrated time delay of 0.5 ps μA^{-1}.

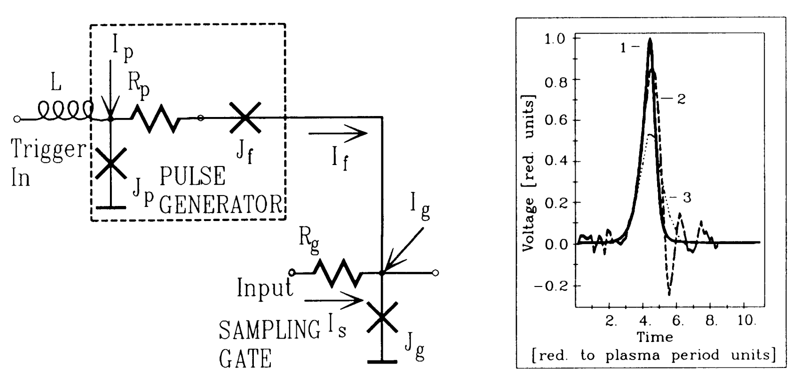
1. Introduction

Short junction switching time suggests that Josephson junctions could be used as samplers. The first samplers (Hamilton *et al* 1989, McDonald *et al* 1980) were able to reproduce a monotonically increasing part of a repeating signal. Samplers using a Faris pulse generator (Tuckerman 1980, Faris 1980), were able to reproduce both increasing and decreasing fractions of a signal. The shortest time resolution of the samplers to date is about 2.1 ps (Wolf *et al* 1985). Commercially manufactured samplers are described in the literature (Whieley *et al* 1987, 1988).

All the previously designed samplers were based on hysteresis Josephson junctions which needed an AC power supply. Special precision delay circuits were used for signal form reproduction (Harris *et al* 1982). In this report we present a new sampler scheme which is based on shunted Josephson junctions.

2. Calculations

This section concerns computer simulations. To compare the classical sampling technique with the suggested one we have reconstructed a single pulse shape using both samplers. The simulated circuit is presented in figure 1(*a*). The sampler-reproduced signal form was calculated as a maximum output bias current of the



(*a*) (*b*)

Figure 1. (*a*) Equivalent circuit of a hysteresis-based sampler in which is included a two junction strobe generator. $J_p = 3$, $I_p = 2.4$, $R_p = 0.5$, $J_f = 1$, $J_g = 1.5$, $R_g = 5$. The reduced units are employed (see text). (*b*) the pulse under investigation (1) and its reconstruction by a classic sampler (2) and by a shunted sampler (3).

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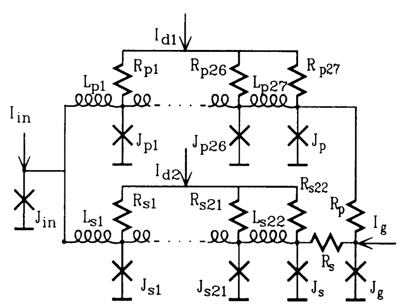
junction when it is not yet switched (Hamilton *et al* 1981). A special program for personal computers was designed to provide all these simulations. The Josephson junction was represented by a resistive model. The following relative units have been used in simulations (Φ_0, quantum of magnetic flux): current i_c, resistance r, capacitance c, basic units, voltage $v_c = i_c r$, time $t = \Phi_0/2\pi v_c$, inductance $l = \Phi_0/2\pi I_c$. The values of these units depend on the kind of Josephson junction used. Three basic independent units were chosen to make the McCumber–Stuart parameter β_c equal 1.

Figure 1(*b*) shows the signal under investigation (curve 1), which is generated by junction $J_s(\beta = 0.25)$. Curve 2 shows the calculated image of the pulse reproduced by a classical sampler based on hysteresis junctions (see figure 1(*a*)) and curve 3 shows the one reproduced by a shunted sampler. Our simulations show that the shunting of junctions up to $\beta_c \approx 1$ does not lead to the crucial growth of time resolution. The use of a DC power supply is an additional merit of the proposed scheme.

3. Circuit design

Figure 2 shows the equivalent circuit and microphotograph of the test circuit. Junction J_s generates a test pulse. Junction J_{in} generates repetitive pulses which are directed to two transmission lines $J_{p1} - J_{p26}$ and $J_{s1} - J_{s21}$. The generator produces SFQ pulses of a frequency f which is related to the voltage V by the Josephson relation $f = V/\Phi_0$. The pulses are branched into two transmission lines. One of them leads to the strobe pulse generator J_p and the other one to the junction J_s which generates a test pulse. The transmission line presents a sequence of overdamped ($\beta \leqslant 1$) underbiased ($I \leqslant I_c$) Josephson junctions. Synchronous variation of all biased currents causes a change in the time required for pulses to pass through the line, so that it is possible to provide the time delay required.

The pulse generator comprises only one junction. After transmitting an SFQ pulse it returns to the superconducting state due to the shunt resistor. Two pulses, one from the pulse generator J_p and another from the signal junction are added to the current I_g and the result is applied to the sampling gate J_g. When the resulting current exceeds the gate junction critical current the junction J_g switches to the voltage state. The J_g voltage is proportional to the frequency of the generator J_{in}. It means that this circuit is useful only at frequencies corresponding to voltages exceeding a few microvolts.



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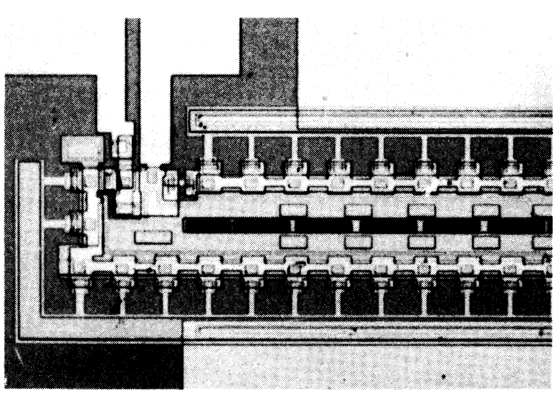

Figure 2. (*a*) The equivalent circuit of experimental sample and (*b*) its photograph. All junctions have the following parameters: characteristic voltage $V_c \approx 100$ μV, voltage is according to the plasma frequency $V_p \approx 95$ μV. Critical currents are $J_p = J_s = J_{in} = 246$ μA, $J_{p1-p26} = J_{s1-s21} = J_g = 164$ μA, $L_{p1-p27} = L_{s1-s22} \approx 1.8$ pH, $R_p = 0.6$ Ω, $R_s \approx 2.8$ Ω.

4. Experimental results

The voltage across the generator J_{in} is set by the current I_{in}. Then a critical value of the current I_g is determined as a function of the current I_{d1} which controls a pulse delay for the line $I_{p1} - I_{p26}$. One of the circuit disadvantages is the strong dependence of the voltage J_{in} on the current I_{d1} caused by the small size of the inductances between the generator and transmission line. So the measurements are reliable only for high voltages when this dependence is negligible. Figure 3(*a*) shows the generator *I–V* curves for two values of I_{d1} corresponding to the extreme points of the curves on figure 3 (*b–e*) representing Josephson generation for

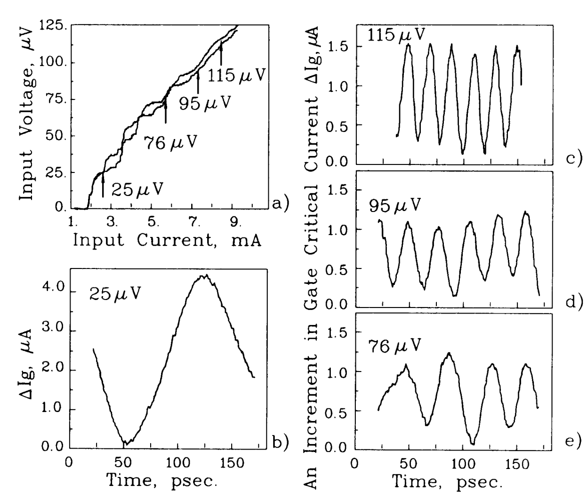

Figure 3. (*a*) Voltage current curves according to two different currents I_{d1} through the delay line. (*b–e*) Experimental observation of Josephson oscillations at different input voltages.

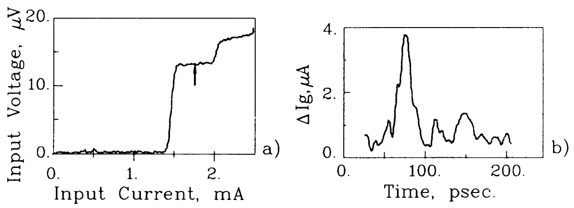

Figure 4. (*a*) The voltage–current curve of the generator and (*b*) the single quantum pulse measured at the point shown.

various generator frequencies. The experimentally measured Josephson oscillation period corresponds to the input voltage value to an accuracy of about 15%. The experimentally determined time delay for 27 junctions equals 0.5 ps μA^{-1}. Some voltage steps of the generator I–V curve appear as a consequence of a high Q-factor, quality transmission line micro-strip.

Finally the time resolution of the circuit was 5 ps (figure 3(*c*)) despite a long plasma period of 20 ps. We have found that the sampler sensitivity is 5 times lower than the theoretical estimate. This may be due to the complicated processes of mutual phase locking (Jain *et al* 1984). The sensitivity is determined in terms of the changes of the critical current I_g. An automatic system keeps the current I_{in} in the middle of the generator I–V curve step (figure 4(*a*)) irrespective of the variations of the current I_{d1}. Figure 4(*b*) represents the results of this measurement regime.

5. Wide frequency band sampler

If the generator frequency is about a few MHz then the gate junction voltage, J_g, is less than 1 μV. To amplify this voltage we can employ the SFQ/DC converter which has already been experimentally investigated (Kaplunenko *et al* 1989).

Pulses from the sampler gate feed the FSQ/DC converter and provide the output voltage of $V_{out}/2$. To create a feedback loop one has to employ a comparator and a rectifier to select the signal equal to $V_{out}/2$ because if a voltage differs from $V_{out}/2$ then the Josephson junction J_g corresponds to the superconducting state. The SFQ/DC output voltage does not depend on the frequency of the coming pulses and it is possible to create a frequency-independent feedback loop for the sampler using the shunted Josephson junctions.

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