SINGLE FLUX QUANTUM VOLTAGE AMPLIFIERS

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The novel elements of the Rapid Single Flux Quantum (RSFQ) logic family – a Quasi Digital Voltage Parallel and Series Amplifiers (QDVA) have been computer simulated, designed and experimentally investigated. The Parallel QDVA consists of six stages and provides multiplication of the input voltage with factor five. The output resistance of the QDVA is five times larger than the input so this amplifier seems to be a good matching stage between RSFQL and usual semiconductor electronics. The series QDVA provides a gain factor four and involves two doublers connected by transmission line. The proposed parallel QDVA can be integrated on the same chip with a SQUID sensor.

INTRODUCTION

The new class of quasidigital circuits has appeared during the experimental investigation of RSFQL elements [1]. These elements provide a logic function with high frequency and due to the Josephson relation between the frequency and voltage, enable transformation of the input voltage by means of a high speed logic operation. Some of these circuits can be utilized as a logic cell for digital devices. For instance the flip–flop is also a high precision voltage divider [2]. Analog function of this cell is provided by the fact that only half of the input SFQ pulses are passed to the output. Another example of the voltage divider with the factors 1/4, 1/2 and 3/4 is the reversible two bit counter slightly changed for the high frequency testing [3]. Theoretically, the modification of n bit reversible counter allows to have the voltages multiple to the factor $1/(2)^n$. It's seems to be useful for the creation parallel analog to digital converters for which the precise voltages are needed. A number of different kind of amplifiers had been theoretically suggested recently [4,5,6], but till now only one of them, based on the direct connections of the Josephson elements idea [6], has been experimentally verified and the voltage doubling has been demonstrated [7]. It enables building two kinds of the Quasi Digital Voltage Amplifiers (QDVA) with higher amplification factor.

Series Josephson voltage amplifier.

a)Theory. The main part of series QDVA is the voltage doubler Fig.1a shows [6,7]. Series connection of n doublers provides the gain factor 2^n. Fig.1b shows the block diagram of the experimentally studied QDVA with n=2. The simulation of this circuit [11] has shown the upper limit of output voltage about $0.6V_c$ ($V_c=I_cR_c$ is the characteristic voltage) independent of the stage number. This restriction is caused by the definite switching time of the load junction J_6 (Fig.1a). The main part of doubler consists of two interferometers $J_2L_2J_5$ and $J_3L_2J_4L_3$ strongly coupled via common inductance L_2. The flux quantum is coming to the input and sequentially switching J_1 and J_2 junctions because the value L_1 is small enough to prevent the trapping of quantum within this interferometer ($J_1L_1<\Phi_0$). The additional phase difference on the ends of the inductance L_2 appears when the fluxon is in contour $J_2L_2L_5$. This difference should be compensated by the clockwise current through the $J_3L_3J_4$. The current decreases the total current for J_3 and increases the bias current for J_4, and as a result antiflux quantum penetrates into the $J_3L_3J_4L_2$. The inductances L_2 and L_3 are small enough to provide the total bias currents in J_3 and J_5 exceeding the corresponding critical values in the presence of quanta which returns the circuit to the initial state after switching J_3 and J_5. One can see that the output voltage is two times larger than the input one.

b) Experiment. Fig.1 shows the equivalent circuits of the series two stage QDVA. Standard trilayer all refractory Nb–AlO$_x$–Nb technology with critical current density ≈1kA/cm^2 has been used for fabrication all of the samples [3]. The junctions have been externally shunted with Mo resistance to provide McCumber parameter β_c≈1. All currents were introduced through the common feed line. An additional adjustment of currents was available to test the different regimes of the circuit operation. Fig.2 shows the experimentally obtained input and output voltages of each cascade as function of the bias current of the Josephson generator J_1. The circuit shows the right operation immediately after introducing the common feed current; but, to get the maximum of output voltage, ≈130μV, one had to put a small adjustment current I_5 which was about 10% of the nominal value. It might be due to the discrepancy between the calculated and real values of critical currents and inductances. Without any adjustment currents, one obtained the output voltage ≈100μV. The maximum of measured voltage 130μV is close to the 150μV theory predicted.

Parallel josephson voltage amplifier.

a)Theory. With the series amplifier, one can imagine logic elements in digital devices, while the parallel one is a completely analog circuit. It is impossible to distinguish the quanta passing trough the different stages of the amplifier. The connection implies the gain factor $_2$n+1, n being the number of cascades [6]. The energy amplification of the quantum, $E=LI_c^2$(L is the inductance of the contour of the quanta localization ; I_c is the minimal critical current of the Josephson junctions the contour involved), is very important in these circuits. The Josephson transmission lines are usually employed for that, but these lines require separate current sources for each of the stages [6]. To overcame this problem a new technique of calculating of the superconductor inductances has been employed [8]. It allows one to consider the inductance as a passive multi–terminal network and build a parallel amplifier which is shown on Fig.3. The circuit consists of a number of levels which are three junction quantum amplification lines. Special layout design enables vertical connections between the interferometers either by the large mutual inductances L_G or by the small one L_S on Fig.3. Two superconductor interferometers, marked on Fig.3 with digits I and II, are strongly coupled due to the L_G, as one needs for the voltage doubler. The SQUIDs III and IV are weakly connected because L_S is small enough (L_S<<L_G) to make neighboring levels independent and to amplify the energy of quantum which is necessary to excite the next stage.

Fig.5. shows the computer simulation of the six stage parallel QDVA. The right operation up to the output voltage of 250μV is found from the time period of passing quantum via one stage. We have $L_S+L_A \approx L_G$ so it's possible to improve the amplifier by reducing the L_S+L_A. Fig.5a shows the layout of the two stages of parallel amplifier. The large coupling inductance L_G is formed by narrow strips of wiring and the weak coupling L_S is formed by the broad base electrode rectangle. Fig.5b shows the simple example of strong coupling between two interferometers due to the common area of currents. A very large distance between interferometers on Fig.5c implies no interaction between them.

The amplifier has n times larger output resistance than the input one. It enables good matching between the SQUID and external electronics. The SQUID is the best input device for the quasidigital circuits because it provides the conversion of a measured signal to the repetition rate of the single flux quanta.

b)Experiment. In experiment we have observed only five stages operated correctly. The introduced bias current on the last cascade (see Fig.3) might destroy the right operation of this stage. Fig.6 shows the voltages on each stage as function of bias current of the input junction. One can see that right operation up to the 250μV is observed. This value is close to the one obtained from computer simulation. An additional adjustment of currents was required to get this voltage because of the parasitic frozen magnetic field.

CONCLUSION

The Josephson analog devices are based on precise calculation of the quanta which are coming to the input. Due to the high internal frequency of calculation, the losing or gaining of some quanta doesn't destroy the analog function. It's the main difference from the digital RSFQ devices for which this effects are critical. Moreover the digital RSFQ circuit should have at least two independent transmission lines for the pulse propagation [1]. One of them is the clock and the other one is the signal line. The lines are connected with the nonlinear impedance of the RSFQ element. Mutual phase locking of the line junctions is due to the nonlinear connection [9]. This problem hasn't been solved yet for RSFQ logic and might it will be the most important one at this area. The same effect may negative for the quasidigital devices also, but for many cases, the phase coupling makes the analog function more stable. For example the coupling of different harmonics takes place for the voltage doubler and voltage divider. In the experiment this phase locking makes larger the margins of bias currents. The interest in complicated Josephson structure nets of junctions and multilayer junctions is great. Parallel amplifier occurs in a net of junctions which are connected by a special way. It's seems that using a quasidigital approach and a technique of organization of inductive coupling, we have found the experimental simulation of more complicate Josephson structures. Principally it will be interesting to built the common theory of quasidigital circuits to provide the different analog functions as one needs.

REFERENCES

1 Likharev K.K, Semenov V.K., RSFQ Logic/Memory Family: a New Josephson-Junction Technology for Sub-Terahertz-Clock-Frequency Digital Systems IEEE Trans. Apl Superconductivity (1991) 1 1 3-28

2 Kaplunenko V.K.,Khabipov M.I., Koshelets V.P., Likharev K.K., Mukhanov O.A. Semenov V.K., Serpuchenko I.L., Vystavkin A.N., Experimental Study of the RSFQ Logic Elements, IEEE Trans on Magn. ,(1989) V. MAG-25, No.2, P. 861-864.3

3 Kaplunenko V.K., Filipenko L.V., Khabipov M.I., Koshelets V.P., Likharev K.K., Mukhanov O.A., Rylov S.V., Semenov V.K., Vystavkin A.N., Experimental Implementation of Analog-to-Digital Converter Based on the Reversible Ripple counter, ASC-90, IEEE Trans. MAG-27,(1991) No 2, pp.2464-2467

4 Semenov V.K., Voronova M.A., DC Voltage Multipliers : a novel application of synchronization in Josephson Junction arrays, IEEE Trans. on Mag.(1989),25 2 1432-1435

5 Semenov V.K , Ext.Abstracts ISEC'87, Tokyo,(1987),138

6 Kaplunenko V.K., Rapid Single Flux Quantum Voltage Multiplier based on Shunted Josephson Junctions, Superconductivity: physics, chemistry, engineering (Soviet journ.),(1991) vol.4, No 4, pp.629-848.

7 V.K. Kaplunenko, V.P. Koshelets,M.I. Khabipov, V.M. Golomidov, S.A. Kovtonyuk, Single flux quantum quasi digital voltage amplifier, Extended abstract of ISEC Glasgow, UK, (1991) 175-1788

8 P.I. Bunyk, A.F. Kirichenko, A.Yu. Kidiyarova-Shevchenko, S.V. Rylov, V.K. Semenov, P.N. Shevchenko To be published

9 Jain A.K., Likharev K.K., Lukens J.E., Sauvageau J.E., Mutual Phase-Locking in Josephson Junction Arrays, Phys. Report 109, (1984) 6 309-426

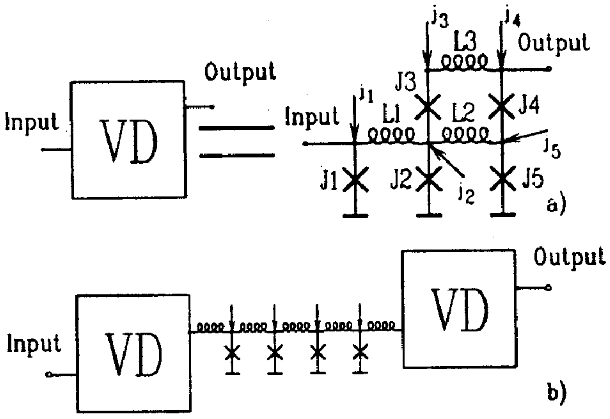

Figure 1 Serial QDVA a) voltage doubler; b) block diagram. $J_1=3J_3$; $J_2=J_5=2J_3=2J_4=300\mu A$; $L_2=20L_3=5.2$pH.; $\beta_c=1$.

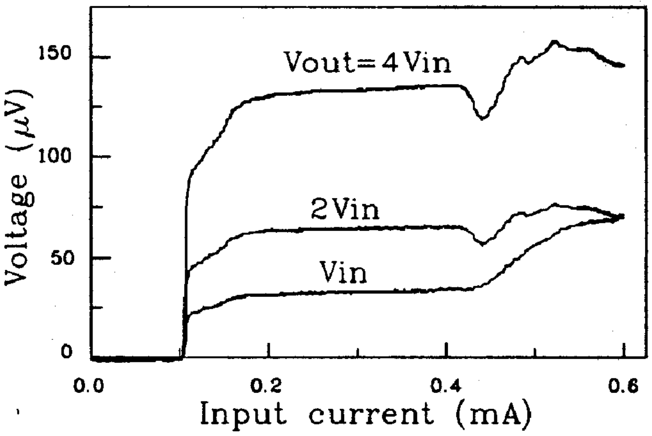

Figure 2 The input V_{in} and the output voltages of each stage vs. bias current of J_1.

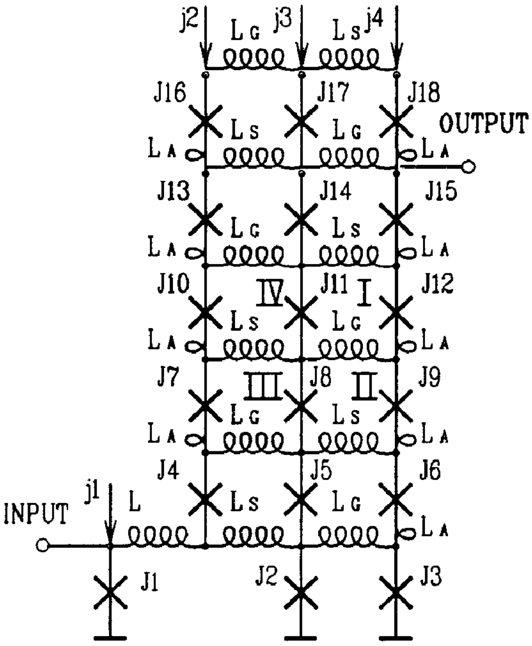

Figure 3 Equivalent circuit of six stage parallel QDVA. $J_2=J_3=J_4=J_9=J_{10}=J_{15}=J_{16}=$ $=220\mu A$; $J_5=J_8=J_{11}=J_{14}=J_{17}=165\mu A$; $J_6=J_7=J_{12}=$ $=J_{13}=J_{18}=110\mu A$; $L_S=0.26$pH; $L_G=$ 4.2pH; $L_A=4.7$pH; $\beta_c=1$.

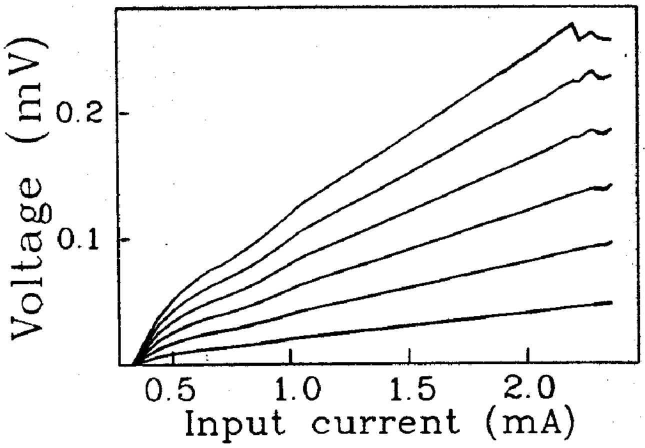

Figure 4 Simulation of parallel QDVA. The voltages of each stages vs. the bias current of the J_1 on Fig.3.

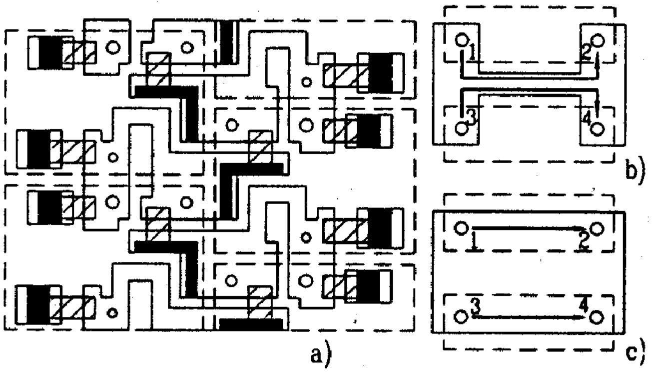

Figure 5 Layout. a) two stages of parallel QDVA; continuous lines – wiring, dashed – base electrode, hatching boxes – shunt resistances, circles–junction areas, filled areas – short connection of electrodes.
b) strong and c) weak interaction between two SQUIDs formed by junctions 1,2 and 3,4.

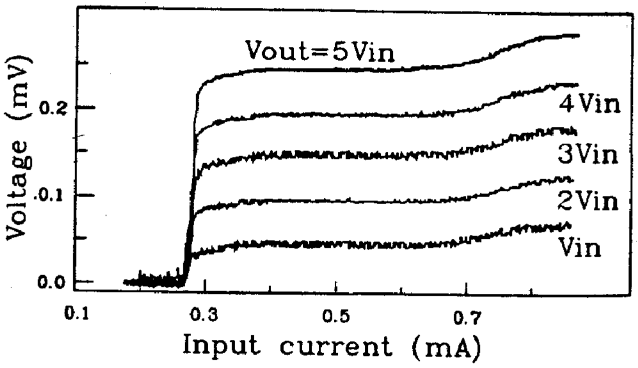

Figure 6 Experimentally obtained voltages on each stage of parallel QDVA vs. bias current of the input junction.