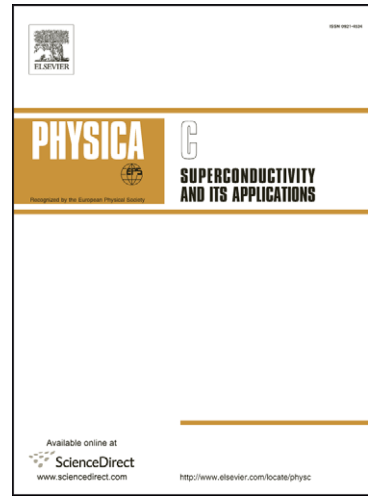

On-Chip RSFQ Microwave pulse generator using a Multi-Flux-Quantum Driver for controlling syperconducting qubits

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ON-CHIP RSFQ MICROWAVE PULSE GENERATOR USING A MULTI-FLUX-QUANTUM DRIVER FOR CONTROLLING SYPERCONDUCTING QUBITS

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Abstract

We have been studying a superconducting quantum-computing system where superconducting Josephson-junction quantum bits (qubits) are controlled and read out by rapid single-flux-quantum (RSFQ) circuits. In this study, we designed and fabricated an on-chip RSFQ microwave pulse generator (MPG), which generates microwave pulses with the time resolution of sub-ns for precise control of qubit states. The output microwave amplitude of the MPG can be amplified to more than 350 μV using a multi-flux-quantum (MFQ) driver, which increases the number of the propagating single-flux-quantum (SFQ) pulses. Fundamental properties of the MFQ driver and the RSFQ MPG were measured at 4.2 K. It was confirmed that the MFQ driver can amplify an SFQ pulse up to six MFQ pulses and the irradiation time and the amplitude of the output microwave of the RSFQ MPG can be controlled adequately.

Keywords: SFQ, quantum bit, superconducting circuits, MFQ

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1. Introduction

Superconducting qubits using Josephson junctions are attractive candidates to realize a quantum computer due to their macroscopic quantum coherence. We have been developing a superconducting quantum-computing system where each qubit is controlled by irradiation of microwave pulses generated by on-chip rapid single-flux-quantum (RSFQ) circuits [1]. Qubits and RSFQ circuits in the system are mainly composed of superconductors, and can be placed at the same temperature stage or on the same chip. In order to control the internal states of qubits precisely, irradiation time of microwave pulses should be controlled with sub-nanosecond time resolution [2, 3]. We propose an RSFQ microwave pulse generator (MPG) to control qubits, which generates microwave pulses on the chip and irradiates them to qubits. The amplitude and pulses length of the generated microwave can be controlled by using a multi-flux-quantum (MFQ) driver and an RSFQ switch respectively. The MFQ driver increases the number of propagating SFQ pulses, thereby the amplitude of the microwave generated by the MPG can be changed approximately from 200 μV to 400 μV. An RSFQ switch, whose operating frequency is up to tens of GHz, turns on and off the output microwave and the pulse length can be controlled with the time resolution of sub-ns. The previously designed RSFQ microwave chopper [1] was not proper to control the multiple-qubit system because it needs several independent microwave generators at room temperature to control each qubit requiring microwave pulses of different frequencies. The proposed MPG, however, can generate microwave on the chip by itself and is suitable for integrating with the multi-qubit system. In this study, we designed and fabricated an RSFQ MPG with an MFQ driver and measured their basic properties.

2. RSFQ microwave pulse generator

2. 1 Principle of operation

Fig. 1 shows a block diagram of an RSFQ MPG. The MPG is composed of a JTL-ring-type RSFQ clock (CLK) generator, an RSFQ switch, a multi-flux-quantum (MFQ) driver, a passive-transmission-line (PTL) driver [4, 5], a superconducting low-pass filter (LPF), and an impedance matching network (IMN). In operation, the train of SFQ pulses generated by the CLK generator is chopped by the RSFQ switch by inputting external start and stop signals, so that SFQ pulses of an arbitrary length can be obtained. The number of the SFQ pulses is increased by the MFQ driver, which amplifies the amplitude of the output microwave as described later. The SFQ pulse train is then passed to the PTL driver and filtered by the LPF to remove higher harmonics. Since the characteristic impedances of the PTL are 2 Ω, the IMN matches it with the impedances (50 Ω) of the coaxial cable, which is used to connect qubit and MPG modules. As a result, microwave pulses of arbitrary lengths are obtained on the chip without a room-temperature semiconductor microwave generator.

The proposed MGP has two important characteristics: (i) it can generate microwave pulses of sub-ns time resolution using on-chip RSFQ circuits, and (ii) the output amplitude is controlled by changing the bias current of the MFQ driver.

2. 2 Design of MFQ driver and RSFQ MPG

An MFQ driver generates MFQ pulses from an SFQ pulse input. The double-flux-quantum driver has been reported in [6], and the proposed MFQ driver is modified version of it. Fig. 2 shows the equivalent circuit of the MFQ driver, where Josephson junctions, J_3, J_4, J_5 are unshunted. J_4 and J_5 switch several times when an SFQ comes into the loop composed of J_2, J_3 and J_4, while J_3 switches at the same time to compensate deficient SFQs in the loop. The number of switching events, and hence the number of output MFQ pulses can be controlled by changing the bias current for the MFQ driver. Fig. 3 shows the dependence of the number of the output SFQ pulses on the bias current of the MFQ driver obtained by circuit simulations. It can be seen that the number of output MFQ pulses generally increases with increase of the bias current, and ranges from one to twelve. Note that the dependence is not a monotonic function and unstable in some bias regions. This is due to the strong nonlinear dynamics of unshunted Josephson junctions.

Fig. 4 shows the simulation results of the MPG using the 5-pole Chebyshev LPF with the cut-off frequency of 6.95 GHz, the ripple of 0.2 dB and the impedance of 2 Ω. The parameters of the LPF are optimized to decrease the group delay for high-speed control of microwave under the condition that the ripple is 0.2 dB and harmonic at 10 GHz is cut off smaller than -20 dB. A high-pass L-type matching network is used to convert 2 Ω to 50 Ω and to remove the DC component, which affects the energy gap levels of qubits. Fig. 4 (a) shows the waveforms and (b) shows the dependence of the amplitude of the output microwave on the number of MFQ pulses. The inset of the Fig. 4 (a) is a magnification of the waveform, which represents three MFQ pulses appear just before the LPF. The output amplitude increases with increase of the density of SFQ pulses because of the superposition of fundamental waves generated from each SFQ pulse. Note that the output microwave is turned on and off using start and stop signals, and the length of microwave pulses can be controlled with the time resolution of sub-ns with sub-ns rise and fall time. The maximum amplitude is larger than 350 μV. The voltage amplitudes referred in this paper are peak-to-peak values.

Large microwave amplitude is necessary for rapid control of qubits within the decoherence time because the Rabi frequency is proportional to the amplitude of the applied microwave. We assumed that the microwave power of lager than 100 pW is needed [7, 8], which corresponds to the amplitude of 100 μV for characteristic impedance of 50 Ω. Therefore, the output amplitude of the MPG is large enough to control qubits. The number of Josephson junctions of the MPG is 131 and power consumption is estimated to be 41.7 μW, which is within the cooling capability of dilution refrigerators [9].

3. Experiment

The MFQ driver and the RSFQ MPG were fabricated using ISTEC standard process (STP2) [10], where superconducting microwave circuits in the MPG were designed precisely using a 3D electromagnetic simulator with two-conductor-layer (2CL) models [11].

We measured basic properties of the MFQ driver and the RSFQ MPG at 4.2 K. Fig. 5 shows the measurement system of the MFQ driver. In the measurement system, an SFQ pulse is amplified to multiple pulses by the MFQ driver. Then the output pulses are hold in the back-pressure JTL, which stores SFQ pulses and outputs them one-by-one when a clock signal is applied. Therefore the number of the stored pulses can be counted. Fig. 6 (a) shows the measured waveforms and represents that the number of output SFQ pulses from the MFQ driver is six. Fig. 6 (b) shows the measured dependence of the output pulse number on the bias current, where only stable bias regions are plotted. It can be seen that an SFQ pulse can be amplified to five or six MFQ pulses. Outside the stable regions, the number of pulses was unstable and not constant, since the circuit is sensitive to the variation of bias current as shown in Fig. 3.

Fig. 7 shows a block diagram of the measurement system and a chip microphotograph of the RSFQ MPG. In order to detect the output signal easily, the output is amplified by 26 dB using a microwave amplifier as shown in Fig. 7 (a). Fig. 8 (a) shows the measured spectrum after the start signal is applied. We confirmed that the output can be switched on and off using start and stop signals. However the output amplitude was not so stable and much smaller than the simulation results shown in Fig. 4 (b). The former is mainly attributed to the unstable operations of the MFQ driver, and the latter to the timing jitter in the JTL-ring-type RSFQ clock generator [12, 13]. Timing jitter makes clock frequency unstable and reduces the quality factor of the output microwave, resulting in broadening of the line width and the reduction of the amplitude. We believe that the instability will be removed by improving the operation of the MFQ driver and by using an on-chip clock generator with smaller jitter. Fig. 8 (b) shows the dependence of the averaged amplitude of the output microwave on the bias current, where averaging time is 100. It should be noted that the output amplitude can be amplified up to 40 μV by changing the bias current for the MFQ driver.

5. Conclusion

We designed and implemented the on-chip RSFQ MPG for the coming superconducting multi-qubit system using Josephson junctions. The MPG generates microwave pulses whose amplitude can be controlled using the MFQ driver. We confirmed that the MFQ driver increases an SFQ pulse up to five or six MFQ pulses.

The MPG produces microwave pulses without a room-temperature semiconductor microwave generator. This ability is quite important for multiple-qubit system because previously designed microwave chopper needed room-temperature microwave generators. We also confirmed that the output amplitude of the RSFQ MPG can be controlled by changing the bias current of the MFQ driver.

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Figure Captions

Fig. 1 Block diagram of the RSFQ MPG.

Fig. 2 Equivalent circuit of the MFQ driver. $J_1 = J_6 = J_7 = 216$ μA, $J_2 = 350$ μA, $J_3 = 360$ μA, $J_4 = J_5 = 400$ μA, $L_{PIN} = 0.312$ pH, $L_1 = 2.223$ pH, $L_2 = 3.000$ pH, $L_3 = 0.783$ pH, $L_4 = 0.871$ pH, $L_5 = 1.066$ pH, $L_6 = 1.495$ pH, $L_7 = 2.790$ pH, $L_8 = 4.749$ pH, $L_9 = 2.010$ pH, $I_{b1} = 300$ μA, $I_{b2} = 427$ μA, $I_{b3} = 390$ μA.

Fig. 3 Simulation results of the MFQ driver. Dependence of the number of SFQ pulses on the bias current is shown. 100 % bias corresponds to the bias current of 1.117 mA.

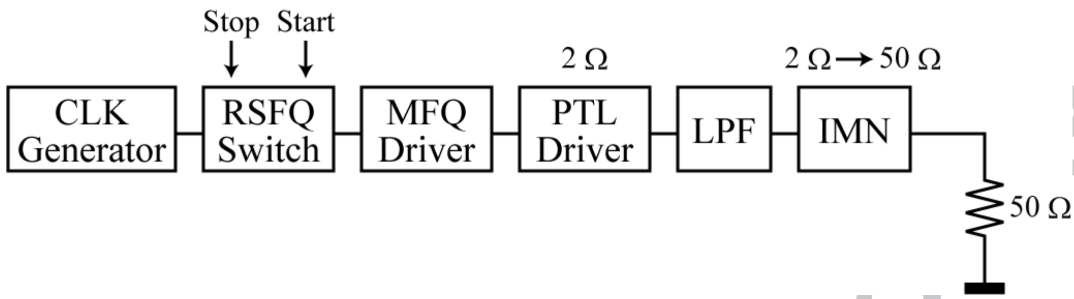
Fig. 4 Simulation results of the RSFQ MPG. (a) Waveforms of the transient analysis. (b) Dependence of the output amplitude on the number of SFQ pulses obtained using the MFQ driver.

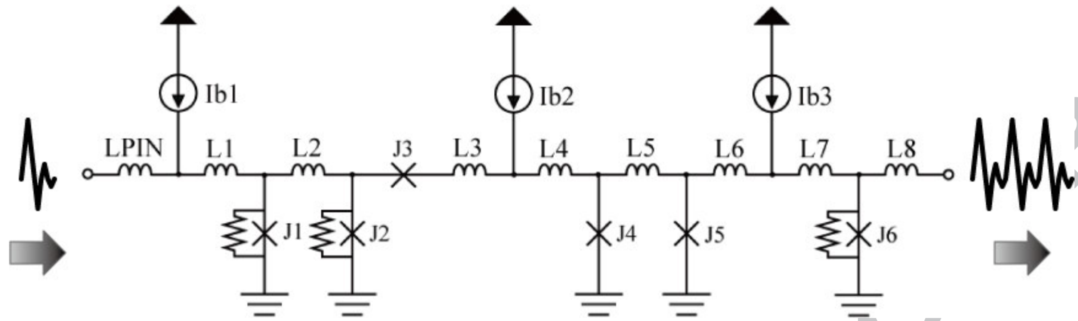
Fig. 5 Measurement system of the MFQ driver. (a) Block diagram of the test circuit. (b) Microphotograph of the MFQ driver.

Fig. 6 Measurement results of the MFQ driver. (a) Measured waveforms. Raising edges in the input signal correspond to the input of an SFQ pulse, whereas transitions in the output signal correspond to the output of an SFQ pulse. The figure shows that an SFQ pulses is converted to six pulses. (b) The number of obtained SFQ pulses versus the bias current.

Fig. 7 Measurement system of the RSFQ MPG. (a) Block diagram of the measurement system. (b) Microphotograph of the MPG chip.

Fig. 8 Measurement results of the RSFQ MPG. The amplitude is amplified by 26 dB. (a) Measured spectrum when the MPG is switched on. The center frequency is 5 GHz, the bandwidth is 500 MHz and the peak is 816 μV. The output is amplified by 26 dB. (b) Averaged output amplitude as a function of the bias current.


Stop
Start
2 Ω
2 Ω → 50 Ω
CLK Generator
RSFQ Switch
MFQ Driver
PTL Driver
LPF
IMN
50 Ω


Ib1
Ib2
Ib3
LPIN
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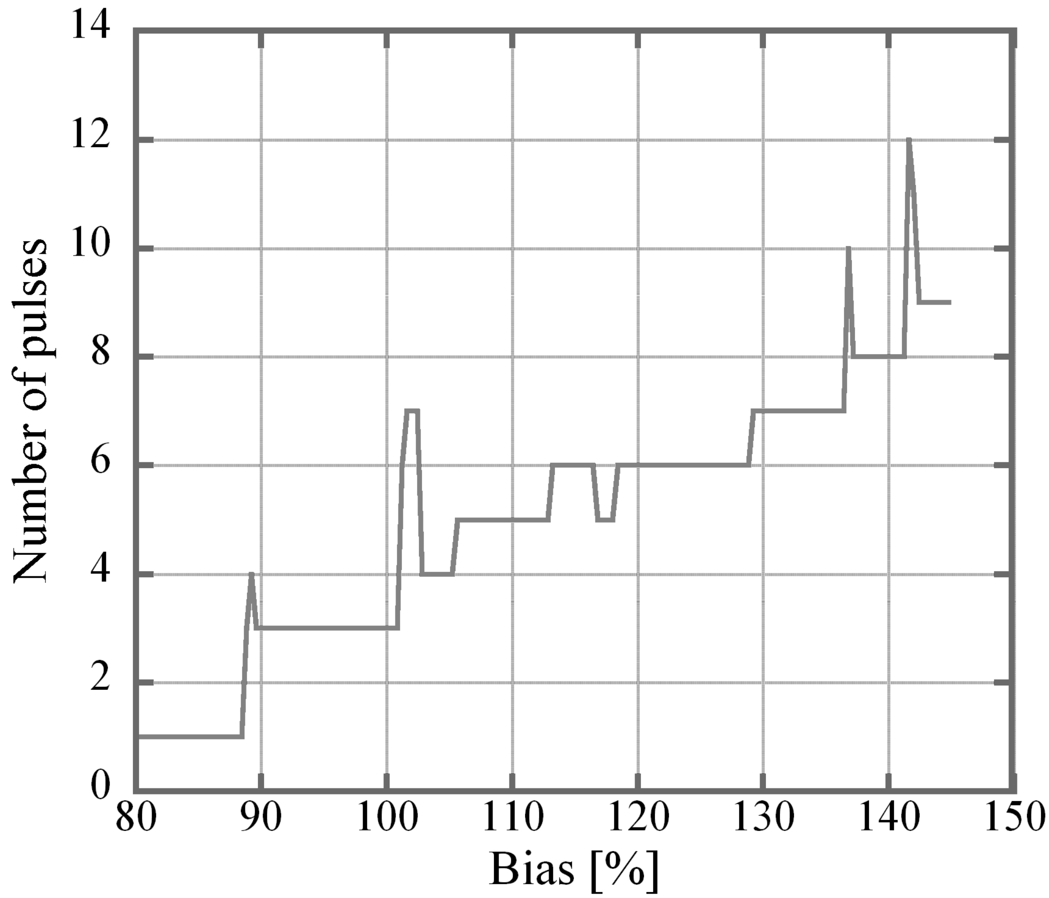
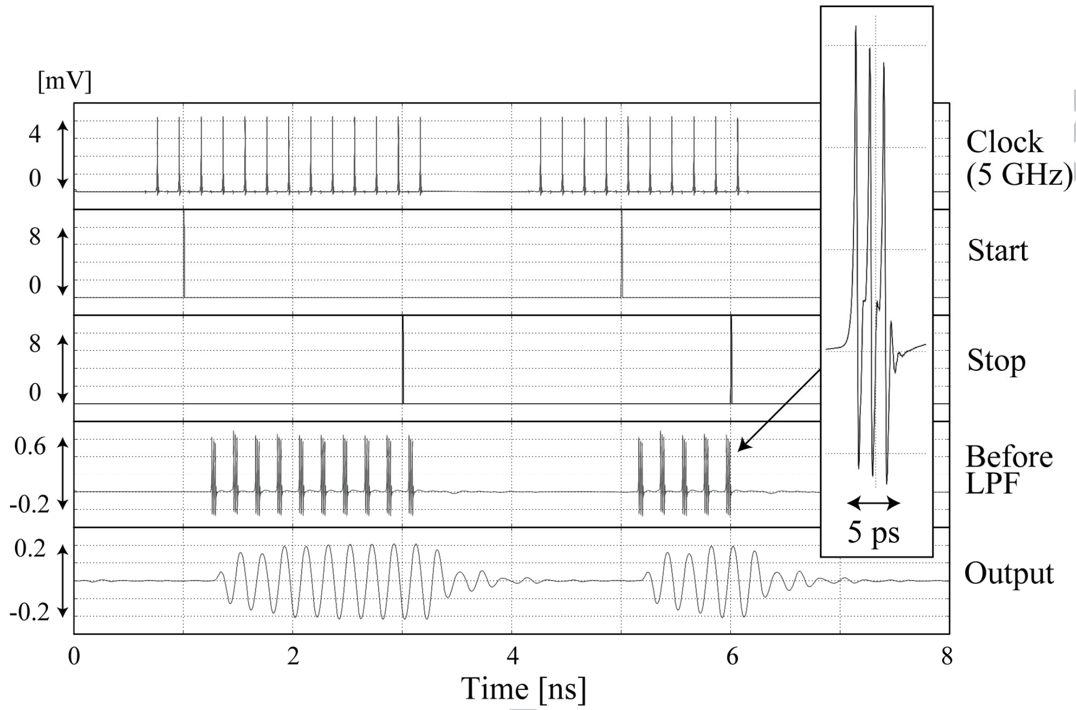
L2
J3
L3
L4
L5
L6
L7
L8
J1
J2
J4
J5
J6



14
12
10
8
6
4
2
0
Number of pulses
80
90
100
110
120
130
140
150
Bias [%]


[mV]
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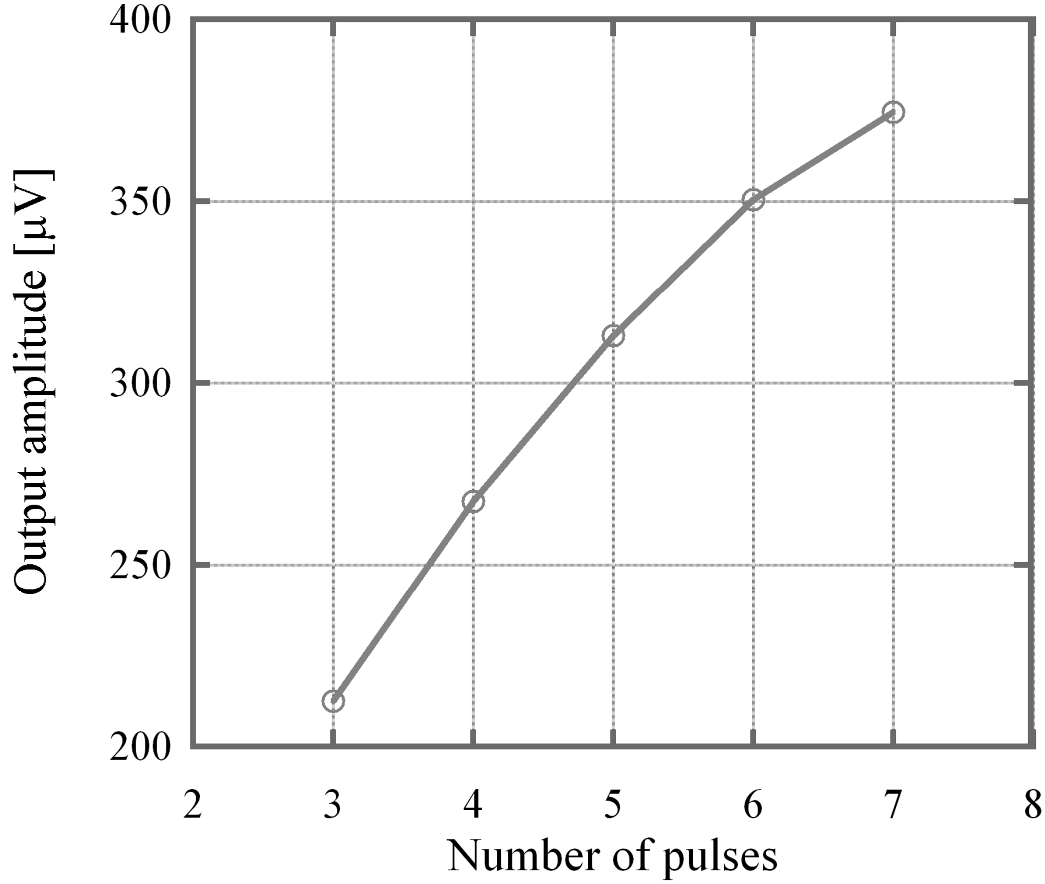
0
8
0
8
0
0.6
-0.2
0.2
-0.2
0
2
4
6
8
Time [ns]
Clock
(5 GHz)
Start
Stop
Before
LPF
Output
5 ps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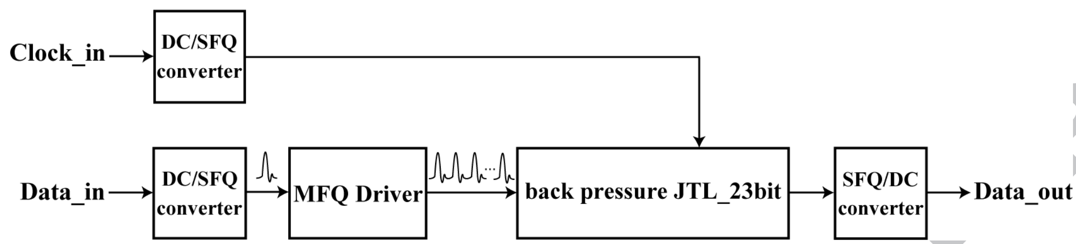
350
300
250
200
Output amplitude [μV]
2
3
4
5
6
7
8
Number of pulses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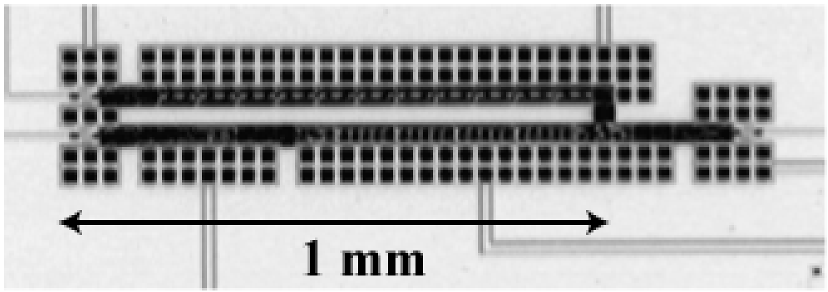
converter
Data_in
DC/SFQ
converter
MFQ Driver
back pressure JTL_23bit
SFQ/DC
converter
Data_out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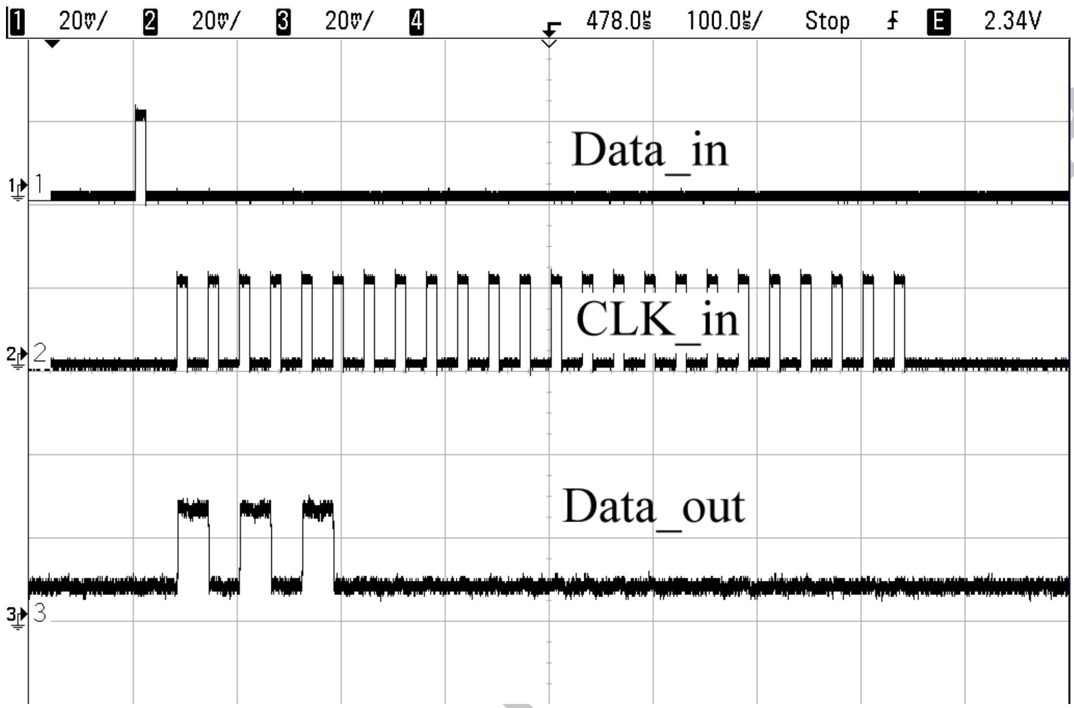
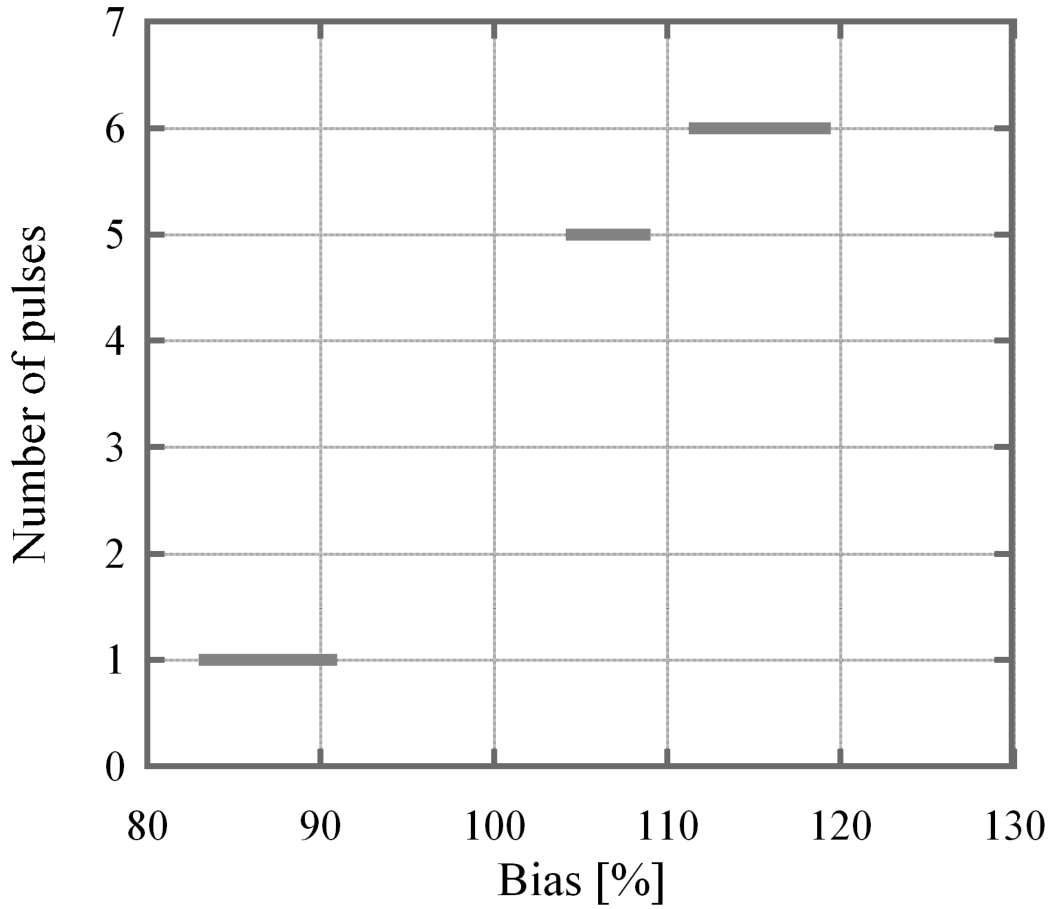


20mV/
20mV/
20mV/
478.0us
100.0us/
Stop
2.34V
Data_in
CLK_in
Data_out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5
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3
2
1
0
Number of pulses
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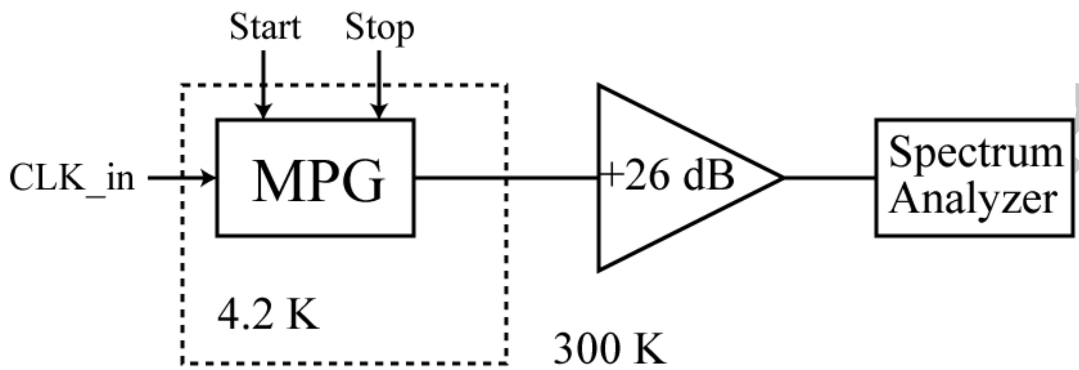
90
100
110
120
130
Bias [%]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Stop
CLK_in
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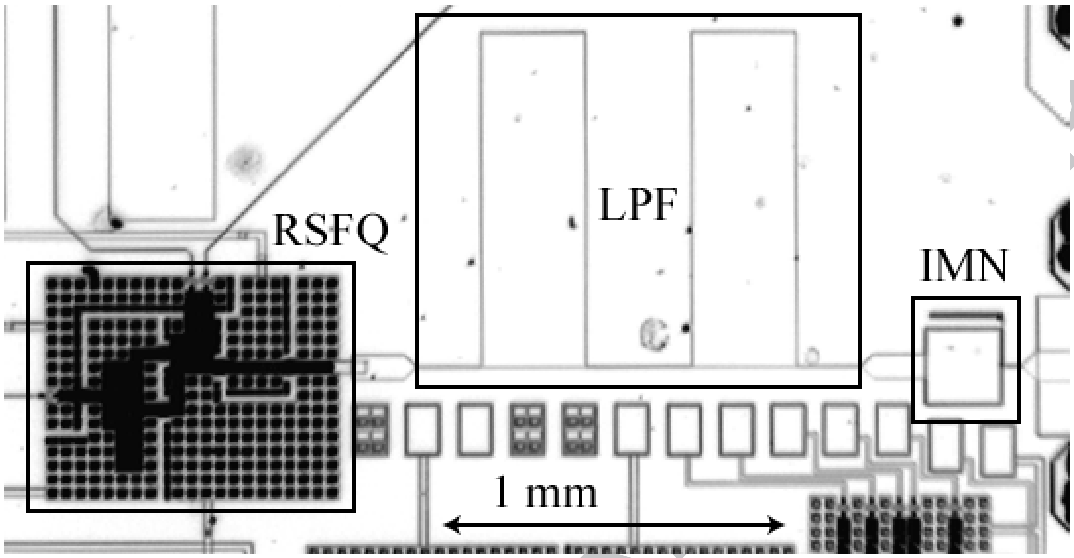
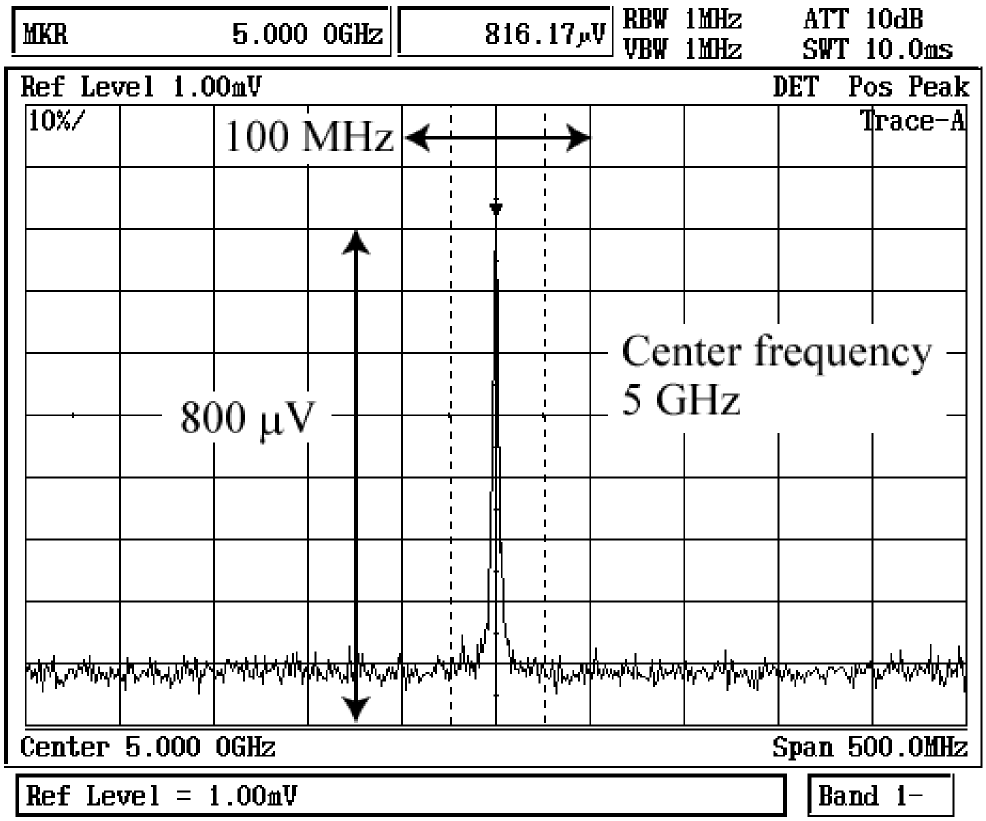
+26 dB
300 K
Spectrum
Analyzer


RSFQ
LPF
IMN
1 mm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RBW 1MHz
VBW 1MHz
ATT 10dB
SWT 10.0ms
Ref Level 1.00mV
DET Pos Peak
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Trace-A
100 MHz
800 μV
Center frequency
5 GHz
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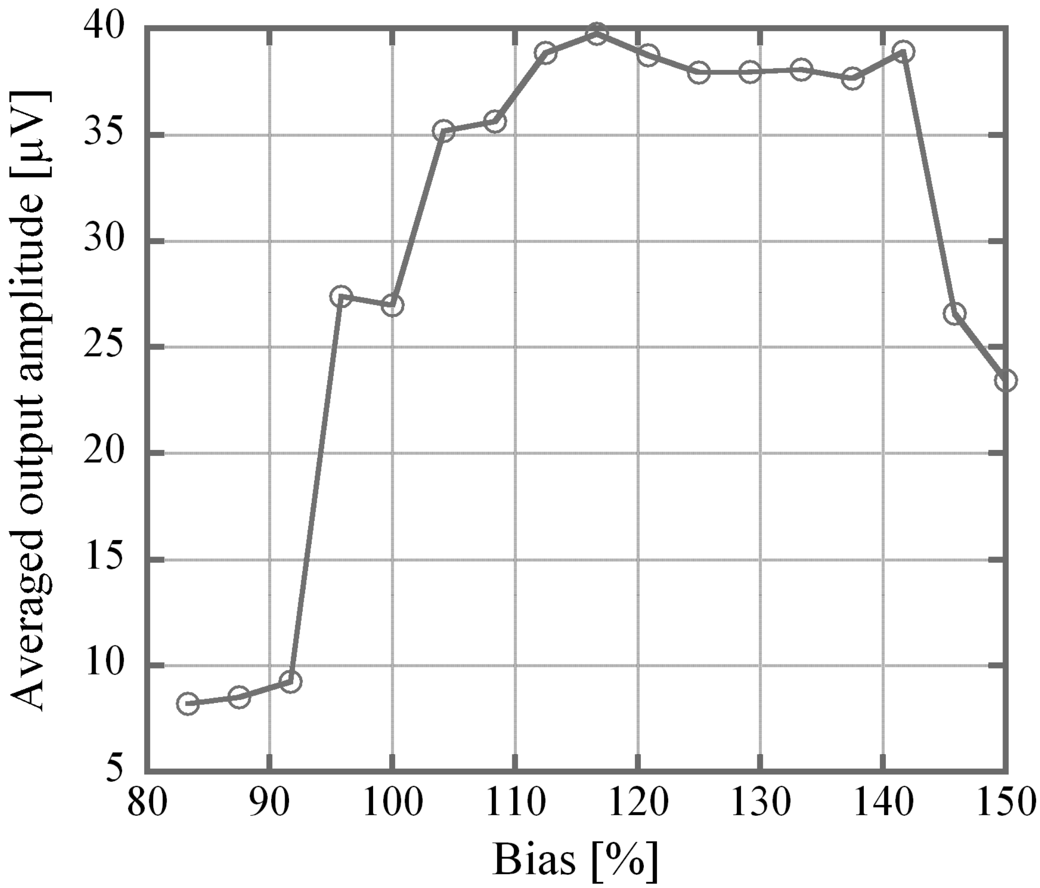
Span 500.0MHz
Ref Level = 1.00mV
Band 1-


40
35
30
25
20
15
10
5
Averaged output amplitude [μV]
80
90
100
110
120
130
140
150
Bias [%]