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► **To cite this version:**

Pascal Febvre, J.-C. Berthet, D. Ney, A. Roussy, J. Tao, et al.. On-chip high-frequency diagnostic of RSFQ logic cells. IEEE Transactions on Applied Superconductivity, 2001, 11 (1), pp.284-287. <10.1109/77.919339>. <hal-04928964v2>

HAL Id: hal-04928964

<https://hal.science/hal-04928964v2>

Submitted on 4 Feb 2025

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On-Chip High-Frequency Diagnostic of RSFQ Logic Cells

Pascal Febvre, Jean-Claude Berthet, David Ney, Agnès Roussy, JunWu Tao, Gilbert Angénieux, Nicolas Hadacek and Jean-Claude Villégier

Abstract—Hilbert Transform spectroscopy is described as a method to analyze the spectrum of pulse trains generated by RSFQ circuits. Simulations are carried out using parameters appropriate for NbN Josephson junctions for both generation and detection of SFQ pulse trains. It is shown that the pulse shape along with the pulse train repetition rate can be extracted through the use of a Josephson junction, used as a spectrometer, and located on-chip with the RSFQ circuit to test.

Index Terms—Hilbert Transform Spectroscopy, Rapid-Single-Flux-Quantum Logic, NbN Josephson junctions, Josephson devices.

I. INTRODUCTION

ELECTRONIC circuits based on superconducting Rapid-Single-Flux-Quantum (RSFQ) logic have attracted much attention due to their intrinsic high speed and low power consumption. They have proven to work up to 750 GHz [1] and different RSFQ-based high-speed circuits have been designed and tested so far for several purposes [2]-[4]. Several difficulties can arise during the design and test of RSFQ circuits. First, the signals generated and processed by such circuits are difficult to measure in real time due to their high intrinsic speed and to the low levels of voltages or currents associated with the SFQ pulses. Indeed, there is no simple interface that can be easily connected to the circuits under test to verify their correct operation at high frequencies. Finally, the measurements have to be non perturbative and performed at cryogenic temperature.

Though some measurements of SFQ pulses have been performed in the past using an electro-optic sampling system [5], such measurements require one to generate pulses in a repetitive way on the superconducting chip in order to perform the autocorrelation of the signal to process. Moreover, such a measurement apparatus has some strong mechanical and thermal constraints to enable the measurements to be performed in a simple and reproducible way. More often, the correct operation of the SFQ circuits is either deduced from dc measurements coupled to accurate behavioral models measurements [1] or are made at low frequencies [2]-[4]. Also, some authors have reported some results with a sampling system based on shunted Josephson junctions which worked up to 50 GHz for some particular signals [6]. In this paper, we propose a method based on Hilbert Transform spectroscopy in order to analyze on-chip some signals, generated or processed by SFQ circuits, which

need to be measured or checked. This method is valid for low-power signals (this condition is verified in most cases for SFQ circuits) that are periodic. In the case of non-periodic signals, it is still possible to use Hilbert Transform spectroscopy under the condition that the signal to measure be windowed within a reasonable time scale (of a few hundred picoseconds) and, then, repeated in a reproducible way.

II. HILBERT TRANSFORM SPECTROSCOPY

In dc voltage-biased Josephson junctions, some oscillations of current or voltage can take place at the Josephson frequency $f_J = 2e/h V$ [7]. The frequencies of the Josephson oscillations range from the microwave to the far-infrared region. This particular property of Josephson junctions is of great interest to analyze incident electromagnetic radiations in this frequency range. Indeed, the Josephson oscillations can be combined (e.g. mixed, down-converted, up-converted, ...) with some external signals by the use of the non-linear properties of the Josephson junctions. Such a possibility has raised some interest in the field of spectroscopy since the frequency of the Josephson oscillations can be controlled by tuning the dc voltage bias of the Josephson device.

In a first step, Hilbert Transform spectroscopy has been proposed and tested using Nb-Nb point contact junctions [8]-[9]. In a second step some resistively-shunted low-Tc Nb/Al-Al₂O₃/Nb junctions have been used to perform spectroscopy in the 75-150 GHz frequency band [10]. Finally, Hilbert spectroscopy has been performed with high-Tc Josephson junctions respectively in the 60-450 GHz band [11], in the 350-850 GHz band [12] and in the 60-2250 GHz range [13]-[14].

The theoretical background of Hilbert Transform spectroscopy can be found in [8] and [9] in the framework of the Resistively-Shunted Junction (RSJ) model. The I-V curve of an RSJ junction receiving a low intensity monochromatic radiation is modified. The change of dc current $\Delta \bar{i}$ for a given dc voltage \bar{v} , is such that:

$$\Delta \bar{i}(\bar{v}, f) = \frac{i_1^2}{8 \bar{i} \bar{v}} \left[\frac{\bar{v} + f}{(\bar{v} + f)^2 + \gamma^2} + \frac{\bar{v} - f}{(\bar{v} - f)^2 + \gamma^2} \right] \quad (1)$$

All currents and voltages in (1) are respectively normalized to the critical current I_c and the critical voltage $V_c = R I_c$ of the Josephson junction. R is the equivalent resistance of the junction normal state resistance in parallel with the shunt resistance.

f is the frequency of the signal and γ is the linewidth of the Josephson oscillations. They are both normalized to the Josephson frequency $2e/h V_c$. \bar{i} is the dc current in the I-V curve without any external radiation, and i_1 is the amplitude of the ac current induced in the junction by the external signal. Equation (1) is valid for $\bar{v}, f \gg \gamma$. Since γ is typically of the order of 1 GHz, this condition is always valid within the frequency range of interest as long as the low voltage part of

This work was supported in part by the programme EMERGENCE of the French Région Rhône-Alpes and by the University of Savoie.

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the I-V curve (below 20 μV) is not taken into account.

In the case of an arbitrary spectrum $S(f)$, formula (1) can be written [8]-[9]:

$$\Delta\bar{i}(\bar{v}) = \frac{\pi}{8\bar{i}\bar{v}} \left[-\frac{1}{\pi} \int_{-\infty}^{+\infty} i_1^2(f) \frac{f-\bar{v}}{(f-\bar{v})^2 + \gamma^2} df \right] \quad (2)$$

$$\text{with } i_1^2(f) = |K(f)|^2 S(f) \quad (3)$$

where $K(f)$ is the transfer function of the circuit connecting the device generating the spectrum to the detector Josephson junction. In (2), the expression between brackets is the Hilbert Transform of $i_1^2(f)$ if the Josephson oscillations linewidth is neglected, which we assume in the following. If one calls this Hilbert transform $g(\bar{v})$, one can write:

$$g(\bar{v}) = \frac{8}{\pi} \bar{i}\bar{v} \Delta\bar{i}(\bar{v}) \quad (4)$$

As a consequence, by measuring the change $\Delta\bar{i}(\bar{v})$ in the dc I-V curve in presence of a signal with an arbitrary spectrum, $g(\bar{v})$ can be estimated and $i_1^2(f)$ can be computed by inverse Hilbert Transform of (4) (see [9]). If the circuit connecting the detector junction to the signal generator is not too frequency-dependent in the frequency range of interest ($K(f) \approx \text{constant}$), then the knowledge of $i_1^2(f)$ directly gives the signal spectrum $S(f)$ according to (3).

Since one is interested in the present case in the analysis of trains of SFQ pulses, the associated spectrum can be broadband, ranging from a few tens of GHz to about 1 THz, which makes the extraction of the spectrum $S(f)$ more difficult. There are two ways to overcome this issue.

The first solution consists of estimating the transfer function $K(f)$ with the help of 3D models. In the case of RSFQ circuits, the circuit can be simpler, like a properly designed transmission line, since the detector junction has to be integrated on-chip with the RSFQ circuits to test.

The other solution is to design this circuit so as the coupling is kept low over the full frequency bandwidth of interest. In this case, $K(f)$ can be assumed to be constant but the drawback is the loss of most of the signal power. This last solution can only be used for train pulses with high enough repetition rates.

At this point, one has to mention that some potential difficulties may arise from the fact that the pulse train generator and detector may be coupled through the microwave circuit of transfer function $K(f)$. In this case, the detector junction, when biased at different current values during I-V curve recording, may react on the generator circuit and generate back some SFQ pulse trains, which may corrupt the overall generator and detector behavior. Consequently, a particular care has to be taken to isolate the detector from the generator via proper couplers or SFQ buffer stages. Moreover, the dc bias of the two circuits must be independent: some dc-block circuits can be designed for that purpose.

III. ANALYSIS OF SFQ PULSE TRAINS

A. Analytic SFQ pulses

In order to evaluate the capabilities of a Hilbert Transform Spectrometer integrated on-chip to analyze some trains of pulses generated by RSFQ circuits, a first step is to assess the performance of Hilbert Transform spectroscopy on a theoretical train of SFQ pulses. This can be done in the case

of a zero-capacitance junction used as a pulse generator, for which the Mc-Cumber parameter β_c is zero. In this case, it is possible to express analytically the phase across the Josephson junction along with the generated voltage across it. It can be shown, see for example [15]-[16], that the voltage is in this case:

$$V(t) = V_{c\text{gen}} \frac{v_{\text{gen}}^2}{i_{\text{gen}} + \cos \left[2\pi \left(\frac{2e}{h} \bar{V}_{\text{gen}} \right) t \right]} \quad (5)$$

where $i_{\text{gen}} = \frac{I_{\text{bias}}}{I_{c\text{gen}}}$, $v_{\text{gen}} = \sqrt{i_{\text{gen}}^2 - 1}$ and

$\bar{V}_{\text{gen}} = v_{\text{gen}} (R I_{c\text{gen}}) = v_{\text{gen}} V_{c\text{gen}}$. i_{gen} is the normalized dc bias current of the Josephson junction, v_{gen} is the related

reduced voltage and \bar{V}_{gen} refers to the average dc voltage across the junction. All indexes *gen* refer to the Josephson junction used as a generator of SFQ pulses. Note that this junction, which generates the SFQ pulse trains that are under investigation, is different from the detector junction, though their current densities are the same since the goal of the detector junction is to be implemented on the chip with the circuits to analyze.

i_{gen} has to be higher than 1 to enable the generation of a train of pulse, associated with a non-zero dc voltage. The repetition rate of the pulses is given by the inverse of the

Josephson frequency $f_J = \frac{2e}{h} \bar{V}_{\text{gen}}$. The maximum voltage

amplitude of each pulse is $2V_{c\text{gen}}$ and is directly dependent of the junction current density and shunt resistance, along with the Full Width at Half-Maximum (FWHM) of each pulse. Indeed, the generation of an SFQ pulse is related to a 2π phase shift so, according to the Josephson relation

$$V(t) = \frac{1}{2\pi} \frac{h}{2e} \frac{\partial \varphi}{\partial t}, \text{ one has } \int_{\varphi_0}^{\varphi_0+2\pi} V(t) dt = \frac{h}{2e} = \Phi_0 \text{ where}$$

$\Phi_0 = 2.07 \cdot 10^{-15}$ Wb is the quantum magnetic flux. To simplify, assuming that the voltage versus time shape of the pulse is rectangular, the related pulse FWHM is $\Phi_0/(2V_c)$. A close-up view of two pulses out of a theoretical pulse train is shown in Fig. 1. The $R I_c$ product of 0.35 mV, used to perform the calculations, has been taken from the current technology available at CEA-Grenoble to fabricate externally-shunted NbN/MgO/NbN junctions with typical current densities of 5 kA/cm² and areas of 4.9 μm^2 [17]. The repetition rate is 20 picoseconds, (oscillation frequency of 50 GHz) and the pulse FWHM is about 3 picoseconds.

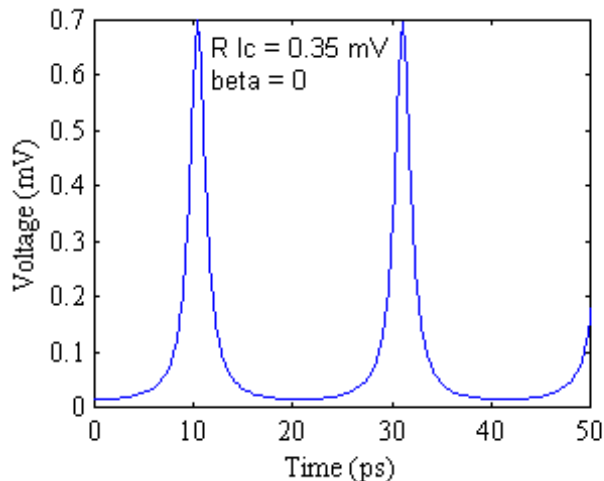


Fig. 1. Theoretical train of SFQ pulses generated by a resistively-shunted Josephson junction and calculated for an $R I_c$ product of 0.35 mV. It corresponds to the technological process for externally-shunted junctions available at CEA-Grenoble. The repetition rate is 20 ps and the SFQ pulse FWHM is about 3 ps.

In a first step, this train of SFQ voltage pulses has been calculated over a 10000 ps window and its Fourier Transform has been computed by using a discrete Fast Fourier Transform algorithm with 32770 points. Since the spectrum associated with the train of voltage pulses has no significant frequency components above the frequency gap of NbN, one has assumed that the pulse train can propagate along any superconducting NbN transmission line without any attenuation or dispersion. However, it is possible, if necessary, to take into account the complex transfer function of the transmission line if losses cannot be ignored.

In a second step, the spectrum associated with the current pulses has been calculated assuming that the transmission line has a characteristic impedance of 2 ohms which is a typical value for interconnection lines between Josephson junctions in RSFQ circuits. Also, one should point out that this value has to be accurately chosen in order to avoid the reflection of the pulses at the ends of the transmission lines [18].

Third, it has been assumed for this study of feasibility that the transfer function of the circuit located between the generator junction and the detector junction was constant and equal to 1. As a result, for each frequency, the calculated power of the spectrum is higher than the power which can be expected for real pulse trains. This difference does not affect the general nature of these calculations as long as the sensitivity of the measurement setup is high enough not to lose any information in the dc I-V curve for noise reasons.

Finally, the expected current change in the detector junction dc I-V curve has been estimated by using (2) to compute the Hilbert Transform of the pulse train current spectrum. It is shown in Fig. 2. An $R I_c$ product of 0.35 mV has been used for the detector Josephson junction. One can notice that the dc current can reach 5 μ A, which can be easily measured experimentally. Also, it can be deduced from some basic signal processing that the shape of the different pulses can be found by analyzing the envelope of the dc current change of Fig. 2 while the voltages at which the dc current changes appear give the repetition rate of the SFQ pulse train.

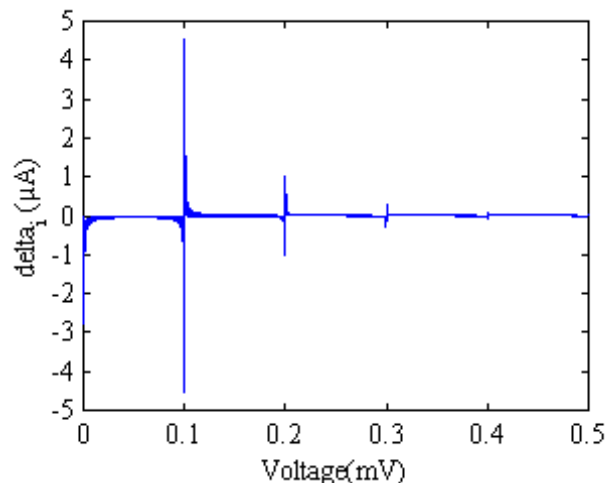


Fig. 2. Expected dc I-V current change induced in the detector junction by the theoretical train pulses shown in Fig. 1. The detector junction $R I_c$ product is 0.35 mV and its area is 4.9 μ m².

The primary goal of Hilbert Transform spectroscopy in this case is to find the frequency spectrum of the pulse train arriving on the detector Josephson junction. Hence, the dc I-V curve of the detector junction in presence of the pulse train has been interpolated and the $g(\bar{V})$ function has been calculated using (4). Then, the inverse Hilbert Transform of $g(\bar{V})$ has been computed to find the spectrum associated with the train pulse. Inverse Fourier Transform is performed in a last step to find the shape of the signal versus time. The recovered pulse train is shown in Fig. 3. The noise in this figure is due to the limitations of the FFT algorithm which provides some artefact signals in the associated power spectrum at frequencies above 600 GHz.

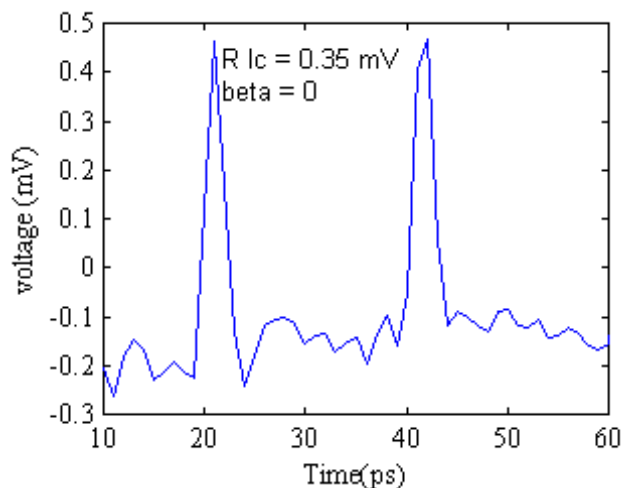


Fig. 3. Recovered pulse train by Hilbert Transform spectroscopy for a theoretical pulse train. The initial FWHM of the pulses of Fig. 1 is accurately recovered along with the pulse repetition rate.

One can see that the shape of the recovered pulses is in good agreement with the theoretical pulse shape. Consequently, Hilbert Transform spectroscopy is a simple way to estimate the width of SFQ pulses as long as the train of SFQ pulses is periodic and the signal powerful enough. One should mention here that this analysis does not take into account any noise source nor the Josephson oscillations linewidth. Indeed, the crucial information to extract in the case of RSFQ circuits is the pulse shape (FWHM and/or maximum voltage); hence the important information mainly relies on the envelope of the dc I-V curve current change.

B. Pulses generated by externally-shunted and self-shunted NbN/MgO/NbN Josephson junctions

Some calculations have also been performed in the case of SFQ pulse trains generated by DC/SFQ converters designed for NbN/MgO/NbN technology [19], and calculated with WinS [20]. Two cases have been studied, which both correspond to the parameters for the fabrication process developed at CEA-Grenoble: 1) for externally-shunted junctions with a McCumber parameter β_c of 1, the area of the 3 junctions of the DC/SFQ converter is $4.9 \mu\text{m}^2$, and the $R I_c$ product is 0.35 mV ; 2) for self-shunted Josephson junctions with an area of $2 \mu\text{m}^2$, the $R I_c$ product is 1 mV and $\beta_c = 3$. A lower repetition rate of about 160 ps (frequency of about 6 GHz) has been chosen in both cases to evaluate the influence of the dc current change of the detector junction. Fig. 4 shows the expected dc current change of the detector junction I-V curve with an incoming pulse train generated by a DC/SFQ converter made of 3 self-shunted NbN/MgO/NbN junctions with a current density of 15 kA/cm^2 . The detector junction has the same features as in previous calculations.

In both cases based on practical RSFQ circuits, as in the case of theoretical pulse trains, the pulse shape can be recovered with a good accuracy.

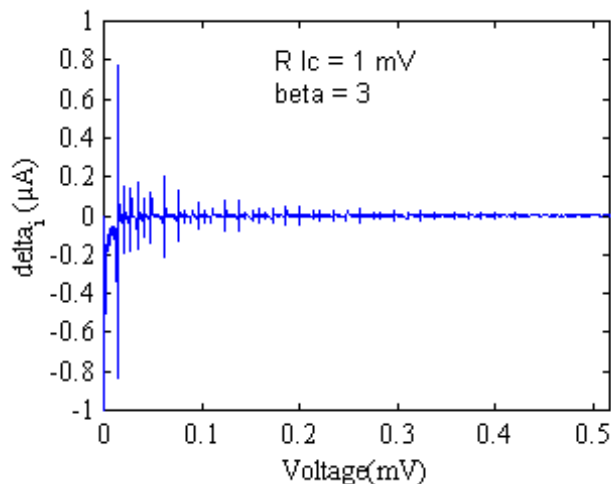


Fig. 4. Expected dc I-V current change induced in the detector junction by a pulse train generated by a DC/SFQ converter made of 3 self-shunted NbN/MgO/NbN junctions. The 3 junctions have an area of $2 \mu\text{m}^2$ and $\beta_c=3$.

IV. CONCLUSION

It has been shown in this study that it is possible to use Hilbert Transform spectroscopy to recover with accuracy the pulse shape and the repetition rate of RSFQ pulse trains. Though, in the case of low repetition rates, the signal power is low and the dc current change in the I-V curve of the detector junction can be lower than $1 \mu\text{A}$ for any dc voltage bias (see Fig. 4). Consequently, this method is more suitable for higher repetition rates, which corresponds to the current trend in the development of RSFQ circuits.

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