Superconducting NbN Band-Pass Filter and Matching Circuit for 30 GHz RSFQ Data Converter

Vratislav Michal¹², Sophie Bouat¹, Jean-Claude Villégier¹ and Jiří Sedláček²

¹ Commissariat à l'Energie Atomique-Minatec, INAC, 17 rue des Martyrs, 38054, Grenoble Cedex-9, France
² BUT, Department of Theoretical and Experimental Electrical Engineering; Kolejní 2906/4, Brno, Czech Republic

vratislav.michal@supelec.fr, jean-claude.villegier@cea.fr, sedlacj@feec.vutbr.cz

Abstract. We present the planar microwave filters developed as the front selective and impedance matching circuit for the RSFQ based (Rapid Single Flux Quantum) A/D converter, operating at cryogenic temperature (T = 9 K). The structures are to be patterned in thin NbN (niobium nitride) superconducting films with critical temperature TC ~ 16 K, on a Si+SiO₂ substrate. The design is experimentally verified at lower frequencies (microstrip, f₀ = 5 GHz) on the Ro3006 substrate. In the design, we aim to reach a high stopband attenuation rate and matching of different input–output impedances (i.e. 50 Ω/50 Ω and 50 Ω/10 Ω). We use a high impedance level in the filter in order to operate with reasonable dimensions of the lines, important for the final accuracy. A layout of first 30 GHz NbN CPW patterned on a 1 cm² chip is presented. This NbN filter is intended for the extraction of the NbN process parameters (kinetic inductance, London penetration depth etc.), in order to improve the accuracy of simulations.

Keywords
Microwave filters, RSFQ logic, RF matching, superconducting electronics, band-pass stub filters.

1. RSFQ Data Converters

The capacity of today’s satellite communication systems directly depends on the performances of Analog-to-digital converters. The architecture based on the software defined radio concept [2] relies on the conversion of input signal, performed at the carrier frequency. In the frequency range up to 100 GHz, the using of RSFQ (Rapid Single Flux Quantum) logic is a promising way, allowing ultrafast data conversion and signal processing [3]. Such direct conversion and signal processing based on the RSFQ logic allow to obtain interesting features, such as low noise, low power consumption, or high versatility of the satellite; this last usually being required by the customers’ specifications. In Fig 1, we show the input stage of our developed 30 GHz A/D RSFQ converter, based on the band-pass type Σ-Δ architecture. The input signal is supplied by the antenna and conditioned by the Low Noise Amplifier and band-pass filter described in this article.

The RSFQ electronic is based on the superconducting Josephson Junctions (JJ) which can reach extremely fast switching time (in order of ps) [2]. In the RSFQ band-pass Σ-Δ A/D converters, the input stage is formed by a one bit modulator (comparator) realized by the JJ (see Fig. 1). The output digital word results from integration performed by the microwave resonator and output decimation filter. In order to provide correct operations of the modulator, the resonator impedance Z₀ has to be close to JJ impedance (≈ several ohms). On this account, the consideration of matching aspect is an important issue of ADC design.

In the following, we describe the basic aspects of superconducting planar circuits design (section II). The structure of 50 Ω/50 Ω and impedance matching 50 Ω/10 Ω filters will be presented in the section III. The geometry of final 30 GHz NbN filter will be presented in section IV.

2. Superconducting Transmission Lines

In the design of microwave filters, the transmission lines (TL) are used basically for the simulation of the resonators or discrete (lumped) elements L, C. Using the superconducting transmission lines (STL) allows to reduce considerably the electrical losses and thus to realize high quality factor resonators (Q >> 100). At high frequencies, however, some new phenomena appear in STL, being absent in the metallic TL. These features arise mainly from the principle of current circulation in a superconductor providing a screening of magnetic field by virtue of the Meissner effect.
In a superconductor, the current circulating is mediated by two electron flows: flow of superconducting electrons (Coppers Pairs CP) and of normal electrons (Quasi Particles QP). It results in a complex behaviour of the superconductor conductivity, having both real and imaginary parts: \( \sigma(\omega) = \sigma_r(\omega) - i \sigma_i(\omega) \). The value of real conductivity is given by the temperature and QP interaction time. Its value follows \( \omega^2 \) tendency and diverges at near zero frequencies. The imaginary part \( \sigma_i \) results from the high scattering velocity of the CP diverges at near zero frequencies. The imaginary part \( \sigma_i \) decreases exponentially from the superconductor surface.

**Fig. 2:** Comparison of experimental effective penetration depth \( \lambda_{eff} \) of thin NbN layers as function of temperature (puttered under different conditions in CEA-INAC [4]).

where \( \mu_0 \) is free-space permeability, \( w \) the line width, and \( t \) the thickness. Accounting the kinetic inductance (3) into a classical transmission line model [7], the characteristic line impedance \( Z_0 \) of STL can be written as:

\[
Z_0 = \sqrt{\frac{G+j\omega C}{(R_s + j\omega L_g + \Sigma L_k)}}
\]

where \( C \) and \( G \) are the capacitance and shunt conductance per unit length, \( R_s \) the surface resistance due \( \sigma_s(\omega, T) \) and \( \Sigma L_k \) the sum of kinetic inductances in the STL. For instance, a microstrip STL of width \( W \) and substrate thickness \( h \) results in characteristic impedance \( Z_0 \) [5, 6]:

\[
Z_0 = \frac{\sqrt{\mu_0 \hbar}}{\sqrt{\varepsilon_0 \varepsilon_r W}} \sqrt{\frac{1 + \lambda_L \text{coth}(t_s/\lambda_L) + \lambda_L \text{coth}(t_g/\lambda_L)}{h}}
\]

where, the \( t_s \) and \( t_g \) are the thickness of the line and the ground plane, respectively and \( \varepsilon_r \) the effective permittivity of the substrate. In addition to the surface conductivity, we account other aspects in the STL design, as the eventual nonlinearities due to magnetic flux trapping and creeping, temperature depending dielectric losses (\( \tan-\delta \)) etc.

### 3. Design of Microwave Filters

A design of the planar band-pass filters can use various structures, such as the coupled resonators (hairpin) or structures based on the TL sections (stubs). In our first design, we aim the 10th order Butterworth filter (with \( f_0 = 5 \text{ GHz} \) and \( BW = 1 \text{ GHz} \)), realized with open \( \lambda/2 \) transmission lines sections. The first filter is realized as matched 50 \( \Omega \)/50 \( \Omega \) filter. In the second design, a binomial impedance transformer was used, in order to achieve 50 \( \Omega \)/10 \( \Omega \) input-output impedance matching with low return losses. The purpose of these 5 GHz filters is to check our optimized geometry before its translation into the NbN 30 GHz CPW filter.

The design of the stub filters is based on transformation of lumped elements RLC prototype. In the low pass-filters, the lumped elements are simulated by the quarter-wave TL (using the Richard’s transformation) and Kuroda’s identity [7]. For the BP filters, LC resonant circuits are simulated by the shorted or open TL resonators.

**Fig. 3:** RLC model of the band-pass filter
The circuit shown in Fig. 4 can be modeled (around the central frequency $f_0$) by the circuit Fig. 4 (right). The method used in the design of our BP filter is demonstrated in Fig. 5 (see e.g. [7]). The blocks $K_i$ from circuit Fig. 5 are the inverters realized by the Fig. 4 $\lambda/4$ TL.

![Fig. 4: Quarter wave transformer used as impedance inverter](image)

The input impedance can be approximated by the following formula [7]:

$$Z_{in} \approx \frac{Z_0}{\alpha + j \beta l}$$  \hspace{1cm} (6)

where $\Delta \omega$ is the deviation from the central frequency $\omega_0$. From (6), the values $L$ and $C$ of equivalent parallel resonant circuit result as: $C = \pi / (2 \cdot Z_0 \Delta \omega_0)$ and $L = \omega_0 / (\omega_0 C)$. If the losses has to be accounted ($\alpha > 0$), the quality factor is defined as $Q = \beta / 2\alpha$. As shown in Fig. 5, the negative capacitors $C_i = -1 / (\omega Z_0)$ are absorbed by the shunted capacitors $C_i$, so that the values of resonant capacitors $C_i$ become $C_i = C_i + C_i / \lambda / 2$. The resonator can be then simulated by the open $\lambda/2$ transmission line of characteristic impedance $Z_0$:

$$Z_0 = \frac{\pi Z_0 \Delta}{2 \cdot g_i}$$  \hspace{1cm} (7)

where $Z_0$ is the impedance of Fig. 4 inverters (i.e. filter impedance level), $\Delta = BW/f_0$ is the fractional bandwidth (= 0.2 in our case) and $g_i$ is value of Fig. 3 RLC prototype.

Optimization of the geometry: The 5 GHz prototypes was patterned on 365 µm thick substrate Ro3006 [1] ($\varepsilon_r = 6.15$) in 17 µm Cu layer. The dimensions of TLs were computed by specialized design software. In the design, we intended to reach high $W/l$ of TL ($> 5$), in order to provide dominant TEM mode. It can be shown, that the first filter design results in low impedances of $Z_{in}$ (e.g. $g_3 \rightarrow Z_{in} = 8 \Omega$, Eq. 7), where corresponding $W/l$ are close to unity. Therefore, the $W/l$ ratio were increased by increasing the impedance level to $Z_0 = 100 \Omega$. For this case, the impedances of TL are ordered in Tab. 1.

![Fig. 5: Transformation of serials arms (Fig. 3) into shunts parallel LC, equivalent lumped-elements electrical circuit (fitting at $f_0$)](image)

![Fig. 6: Final geometry of BP filter. Impedances $Z_{in}$ are tabulated in Tab. 1. ($\lambda/2$ is in order of 14 mm for Ro3006).](image)

However, the values of $W/l$ computed for $Z_0 = 100 \Omega$ are still not satisfying, concerning the $Z_{in}$, $Z_0$ and $Z_{in}$. This is why, two $\lambda/2$ transmission lines are parallel-connected, in order to multiply by factor two the TL impedances $Z_{in} = Z_{in}$ (compare to values in Tab.1, see Fig. 6). This configuration leads to minimal impedance of transmission line $2 \cdot Z_{in} = 31.4 \Omega$ having a satisfying $W/l = 8$.

![Fig. 7: Transfer characteristic $s_{12}$, measured on BP filter from Fig. 6.](image)
The second designed filter is intended to match a low impedance load, in our case $Z_0 = 10 \, \Omega$. The wideband matching of high input/output impedance ratio can be provided by a multi-section transformer \cite{7}. For our fractional bandwidth of $\Delta = 20 \%$, a two section binomial transformer $100 \, \Omega / 10 \, \Omega$ provides sufficiently low return losses ($|\Gamma| < 0.02$) within the pass-band area. Note, when the matching of higher impedances than $10 \, \Omega$ is required, the line sections computed by the binomial (or e.g. Tchebychev) polynomials can form directly the impedance inverters of the filter; the $Z_0$ of stubs Eq.(7) are then computed for $Z_0$ equal to geometric mean of neighbours’ impedance inverters impedances.

In order to provide a layout of our final 30 GHz superconducting CPW filter, the configuration presented in previous section (Fig. 6) was transformed in the CPW, with accounted aspect of STL design (section 2). The filter shown in Fig. 9 is intended to provide a characterization of our NbN process in temperature range between 4 and 10 Kelvins. We were interested namely to determine the values of $\varepsilon_r$, $\tan-\delta$ of Si +SiO$_2$ substrate, $L_K$ and surface resistance of the NbN layers. This step enables important improvement of the simulation accuracy, required for our design of 50 $\Omega$/2 $\Omega$ filters and part of superconducting resonator of ADC (Fig. 1). Fig. 9 shows a layout using the TL impedances mentioned in Tab. 1. To avoid the influences of environments (e.g. presence of liquid He or He vapours), we use a narrow isolating gap of the CPW STL (in order of tens of $\mu$m). With this method, the dominant dielectric constant is given by the Si+SiO$_2$ and the CPW lines can exhibit favourable properties, such as good stopband attenuation and low inserting and return losses. The cryogenic test of designed NbN superconducting CPW filters at 9 K is under preparation in order to extract the RF parameters of the process.

4. Design of 30 GHz CPW filter

In order to provide a layout of our final 30 GHz superconducting filter, the configuration presented in previous section (Fig. 6) was transformed in the CPW, with accounted aspect of STL design (section 2). The filter shown in Fig. 9 is intended to provide a characterization of our NbN process in temperature range between 4 and 10 Kelvins. We were interested namely to determine the values of $\varepsilon_r$, $\tan-\delta$ of Si +SiO$_2$ substrate, $L_K$ and surface resistance of the NbN layers. This step enables important improvement of the simulation accuracy, required for our design of 50 $\Omega$/2 $\Omega$ filters and part of superconducting resonator of ADC (Fig. 1). Fig. 9 shows a layout using the TL impedances mentioned in Tab. 1. To avoid the influences of environments (e.g. presence of liquid He or He vapours), we use a narrow isolating gap of the CPW STL (in order of tens of $\mu$m). With this method, the dominant dielectric constant is given by the Si+SiO$_2$ and the CPW lines can exhibit favourable properties, such as good stopband attenuation and low inserting and return losses. The cryogenic test of designed NbN superconducting CPW filters at 9 K is under preparation in order to extract the RF parameters of the process.

5. Conclusion

In this article, we present a design of 5 GHz and 30 GHz band-pass filters with 20 % fractional bandwidth. The filters were designed for matched (50 $\Omega$/50 $\Omega$) and unmatched (50 $\Omega$/10 $\Omega$) circuits, allowing connection of the low impedance Josephson junction modulator. The filters use high internal impedances levels allowing to design the lines with reasonable dimensions. The tests provided on the 5 GHz samples have shown decent RF properties, such as good stopband attenuation and low inserting and return losses. The cryogenic test of designed NbN superconducting CPW filters at 9 K is under preparation in order to extract the RF parameters of the process.

Acknowledgment

This Work is supported by the ANR-TCOM-06 023 ‘HyperSCAN’ project. We would thank D. Renaud from CEA-LETI/DPTS plateform for its inputs and A. Monfardini, Institut Neel, CNRS-Grenoble for support in the 5 GHz prototype fabrication on Ro3006 substrates.

References


