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Application of a broadband Josephson parametric amplifier

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Abstract. We examine the performance of a Josephson Parametric Amplifier (JPA) which uses an array of SNAILs (Superconducting Nonlinear Asymmetric Inductive eLements) as the source of nonlinearity and leverages the technique of impedance engineering (introducing a positive linear slope in the imaginary part of the input impedance seen by the SNAILs) to overcome a traditional gain-bandwidth product and increase the 1-dB compression point. We experimentally demonstrate an 18 dB gain over a 586 MHz band, along with a 1-dB compression point -101.9 dBm. All these characteristics are of great importance for the quantum devices measurements and in particular for the single-shot readout of a multi-qubit system. The signal-to-noise ratio after the application of the JPA was increased by 3 times. That led to the improvement of separation fidelity of single-shot dispersive measurements of a transmon qubit from 30.6% to 97.2%.

Keywords: parametric amplifier, Josephson junction, gain-bandwidth product, 1-dB compression point, single-shot readout

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Применение широкополосного джозефсоновского параметрического усилителя

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Аннотация. В данной работе исследуется применение широкополосного джозефсоновского параметрического усилителя на основе сверхпроводящих нелинейных асимметричных индуктивных элементов SNAIL в качестве источника нелинейности и с использованием техники трансформации импеданса (введение частотной зависимости мнимой части входного импеданса) для увеличения gain-bandwidth product и мощности насыщения. Были экспериментально продемонстрированы коэффициент усиления 18 дБ в полосе 586 МГц и мощность насыщения -101.9 дБм. Эти характеристики очень важны для измерений квантовых устройств, и в частности для проективного считывания многокубитной системы. Благодаря использованию усилителя отношение сигнал-шум измерительной цепи было увеличено в три раза. Это привело к улучшению точности погрешности разделения состояний проективного дисперсионного считывания кубита-трансмона с 30.6% до 97.2%.

Ключевые слова: параметрический усилитель, джозефсоновский переход, мощность насыщения, дисперсионное считывание

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Introduction

As the field of quantum computing is rapidly evolving, quantum devices incorporate more and more qubits, inevitably forming a demand for broadband parametric amplifiers which can be used for multiplexed qubit readout. Commercially available HEMT amplifiers are not sufficient because of high added noise, T_{HEMT} =3–5 K. Josephson Parametric Amplifiers (JPAs) are capable of reaching the minimum added noise imposed by quantum mechanics, T_q ~ 0.3 K, and consequently can increase the signal-to-noise ratio (SNR) several-fold. Enhancement of SNR is a vital task for qubit measurements because it allows to speed up readout and improve the fidelity.

Moreover, JPAs have to provide a decent gain G_{JPA} to overcome the noise from the subsequent HEMT amplifiers, as follows from the expression for the chain noise:

$$T_{\text{chain}} = T_{\text{JPA}} + \frac{T_{\text{HEMT}}}{G_{\text{JPA}}}. \quad (1)$$

Thus, the crucial requirements which define the performance of the JPA are low added noise, high gain (15–20 dB), large bandwidth and dynamic range, as well as ease of operation.

Generally, a parametric amplifier is just a nonlinear oscillator, where the nonlinearity provides the power transfer from the strong pump to the weak quantum signal. JPAs employ the Josephson junctions (JJs) to introduce the required nonlinearity: their inductance depends on the phase drop φ across the JJ as

$$L_J = \frac{\Phi_0 / I_0}{\cos(\varphi)},$$

where Φ_0 is a magnetic flux quantum and I_0 is the junction's critical current.

The performance of JPAs is fundamentally confined by several factors. First of all, there is a trade-off between the power gain and the bandwidth of amplification, namely the 'gain-bandwidth product' [1]:

$$G = 1 + \frac{G_{max} - 1}{1 + \left(\omega / \Gamma\right)^2}, \ \Gamma \propto \frac{1}{\sqrt{G_{max} - 1}}. \quad (2)$$

Thus, there is no sense to strive to reach the gain more than 15-20 dB because that is enough to overcome the noise from HEMT amplifiers and further increase in gain will just lead to the decrease in bandwidth.

Next, the amplification decreases at high signal powers as it is provided by plentiful though still depletable photons from the pump. To quantify this effect, the so-called 1-dB compression point is introduced as the signal power at which the gain drops by 1 dB.

Seeking the way to sidestep negative influence of the aforementioned factors, we study a JPA which uses an array of M = 23 SNAILs (Superconducting Nonlinear Asymmetric eLements) as a nonlinear element [2]. This architecture offers great flexibility while designing the device. A single SNAIL consists of 3 large Josephson junctions (inductance L_J) in a loop with one smaller junction (inductance L_J/α) (Fig. 1).

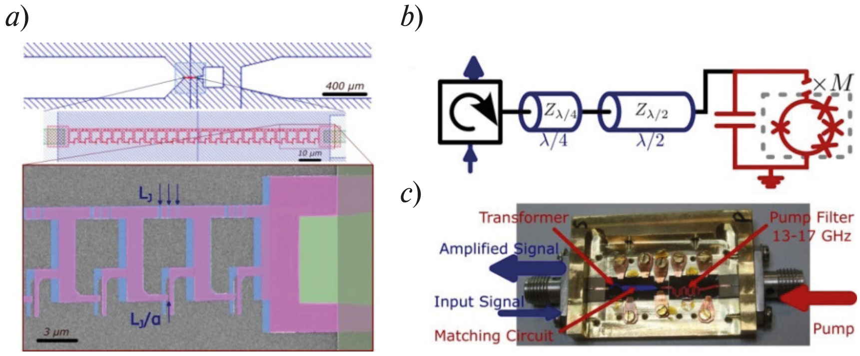

Fig. 1. Design (top) and false color scanning electron micrograph (bottom) of the structure (*a*); the Al-based tunnel junctions are shaded in pink and blue for two different evaporation angles, respectively. Nonlinear resonator composed of a capacitively shunted SNAIL array (red) coupled to the source impedance via two transmission line segments (blue) introducing a positive linear slope in the imaginary part of the input impedance $Z_{in}[\omega]$ (*b*). Implementation of the circuit in (*b*) using microstrip geometry (*c*); the transformer and the pump filter are fabricated on separate chips

The Hamiltonian of such amplifier can be approximated as [2]:

$$\frac{H_{\text{JPA}}}{\hbar} = \omega_a \hat{a}^\dagger \hat{a} + g_3\left(\hat{a} + \hat{a}^\dagger\right)^3 + g_4\left(\hat{a} + \hat{a}^\dagger\right)^4. \quad (3)$$

Then the power gain for a signal at frequency ω_s and the pump at ω_p is

$$G[\omega] = 1 + \frac{4\kappa^2 |g|^2}{\left(\Delta_p^2 - \omega^2 + \frac{\kappa^2}{4} - 4|g|^2\right)^2 + \left(\kappa\omega\right)^2}, \quad (4)$$

where $\omega = \omega_s - \frac{\omega_p}{2}$, $g = 2g_3\alpha_p$, $\Delta_p = \omega_a - \frac{\omega_p}{2} + \frac{32}{3} g_4 |\alpha_p|^2$;

α_p is the mean intracavity amplitude and κ is the dissipation rate defined by coupling to the transmission line. The performance of an amplifier depends only on ω_a, g_3, g_4 and κ, which can be tuned via engineering L_J, M, α, ω_0.

The expression for $G[\omega]$ (4) may lead to a confusion that the gain-bandwidth product can be set arbitrarily large by applying a stronger pump. However, that is not so. Higher-order terms will appear in Hamiltonian (3) with the extreme increase in pump power making the further analysis invalid. Moreover, as regards experimental setup, huge pump may cause the increase in the cryostat base temperature and interfere with the experimental process.

The device under study leverages another technique to go beyond the gain-bandwidth product, impedance engineering [1]. The design uses a combination of a $\lambda/4$ and a $\lambda/2$ impedance transformers to introduce the frequency dependence of the environmental impedance:

$$Z_{in}[\omega] = R + i\xi\omega. \quad (5)$$

It turns out that by tuning ξ it is possible to eliminate the leading-order quadratic dependence of $G[\omega]$.

Thereby the modified gain-bandwidth product can be rewritten as:

$$\tilde{G}[\omega] = 1 + \frac{G_{max} - 1}{1 + \left(\omega / \tilde{\Gamma}\right)^4}, \ \tilde{\Gamma} \propto \frac{1}{\sqrt[4]{G_{max} - 1}}. \tag{6}$$

As one can see, application of impedance engineering makes the trade-off between gain and bandwidth less severe.

SNR measurement can be used to estimate the JPA's added noise. When the pump is off JPA provides no amplification so the only active amplifiers in the chain are HEMTs:

$$SNR_{\text{HEMT}} = \frac{A}{T_{\text{HEMT}}}. \tag{7}$$

After turning the pump on, the signal A is amplified in JPA as well:

$$SNR_{\text{JPA}} = \frac{G_{\text{HEMT}} G_{\text{JPA}} A}{G_{\text{HEMT}} G_{\text{JPA}} T_{\text{JPA}} + G_{\text{HEMT}} T_{\text{HEMT}}} = \frac{A}{T_{\text{JPA}} + \dfrac{T_{\text{HEMT}}}{G_{\text{JPA}}}} \equiv \frac{A}{T_{\text{chain}}}. \tag{8}$$

Combining (7) and (8),

$$T_{\text{JPA}} = T_{\text{HEMT}} \frac{SNR_{\text{HEMT}}}{SNR_{\text{JPA}}} - \frac{T_{\text{HEMT}}}{G_{\text{JPA}}}. \tag{9}$$

Eq. (9) provides an easy way to learn T_{JPA} in situ.

Materials and Methods

The fabrication of the device starts with the aluminum evaporation on a silicon substrate followed by etching of a patterned optical resist mask in Cl_2 plasma. To minimize the amount of native oxide on silicon substrate, piranha solution and buffered HF treatment were implemented [3]. The Josephson junctions for the device were fabricated using electron lithography and the aluminum was evaporated using Dolan bridge technique [4].

Results and Discussion

The characterization is done by monitoring the transmission through the amplifier while sweeping the signal frequency and the pump power. The results are shown in Fig. 2,*a*. The flattest gain profile is shown in Fig. 2,*b*. The saturation power measurement is shown in Fig. 2,*c*, demonstrating the high 1-dB compression point −101.9 dBm which is on par with the best reported amplifiers [2], [1].

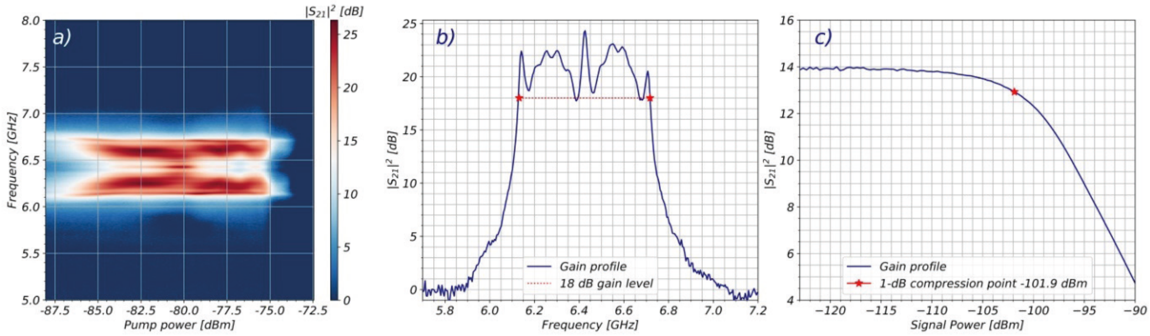

Fig. 2. Characterization of amplifier: amplification (color) versus signal frequency and pump power (*a*), the huge bandwidth is detected in a wide range on the pump power scale; slice of the dependence in (*a*) at the pump power -80 dBm (*b*), 18 dB gain is reached in a bandwidth of 586 MHz; 1-dB compression point measurement (*c*) (signal frequency 7.34 GHz)

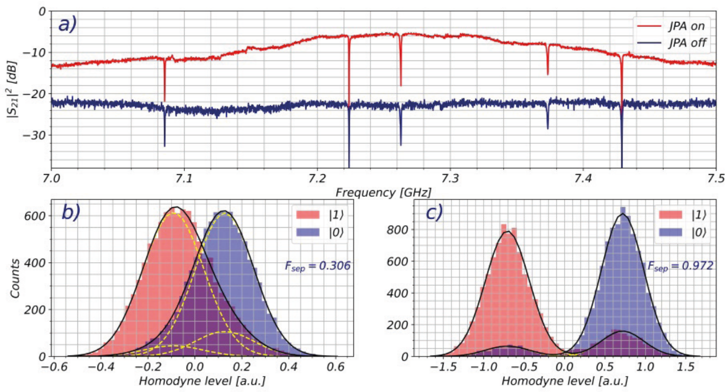

Fig. 3. Application of the amplifier. Comparison between the transmission profiles through the readout line of the 5-qubit sample with active JPA (red, pump signal on) and inactive (blue, pump signal off) (*a*): in 'off'-state, the JPA has almost no effect on transmission. The SNR at resonator frequencies (sharp dips in transmission) in 'on'-state is increased by approximately 3 times (see Table 1). Applying the device for single-shot qubit measurements (resonator II at 7.232 GHz) (*b*): the $|0\rangle$ and $|1\rangle$ states are nearly indistinguishable after I-pulse (blue) and π-pulse (red) without JPA (*b*) providing poor separation fidelity of 30.6%. After turning on the JPA, the state histograms become well-separated with decent fidelity of 97.2% (*c*)

For the ease of application of the amplifier for any quantum device the optimization algorithm was developed. It takes as input the needed gain and bandwidth and seeks for the parameters (bias magnetic flux, pump frequency and power) which provide the best performance. Using it, a suitable working regime for a 5-qubit device was found. The improvement of the SNR is shown in Fig. 3,*a*. Due to improved SNR, the fidelity of single-shot IQ-clouds measurement [5] was also enhanced (Fig. 3 *b*, *c*).

The SNR was measured for the resonant frequencies of the resonators for dispersive readout. Results are shown in Table 1. It can be seen that a three-fold increase in SNR was achieved in the entire band. According to Eq. (9), one can estimate the additional noise of JPA knowing the $T_{\text{HEMT}} \approx 5$ K : $T_{\text{JPA}} \approx 0.4$ K which is comparable to the quantum noise.

Table 1

Improvement of SNR for resonant frequencies

Frequency (GHz)	$\text{SNR}_{\text{JPA off}}$	$\text{SNR}_{\text{JPA on}}$	$\text{SNR}_{\text{JPA off}}/\text{SNR}_{\text{JPA on}}$
7.086	16.6	47.2	2.8
7.232	19.0	61.9	3.3
7.262	16.4	48.4	2.9
7.374	17.9	54.1	3.0
7.429	7.3	20.4	2.8

Conclusion

The performance of the Josephson Parametric Amplifier was examined. The design leveraging the techniques of SNAILs and Impedance Engineering allows for high 1-dB compression point -101.9 dBm and power gain 18 dB in a bandwidth 586 MHz. The amplifier was used for the measurement of a 5-qubit processor. It tripled the signal-to-noise ratio and increased the separation fidelity of single-shot measurements from 30.6% to 97.2%.

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