PARAMETRIC AMPLIFICATION USING NONLINEARITY OF A QUBIT

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Received 30 April 2013; accepted 06 May 2013

1. Introduction

For very precise quantum limited measurements, microwave amplifiers with high gain and low added noise are key element [1]. Nowadays, state of the art cryogenic microwave amplifiers reach gain up to 40 dB, while their noise temperature is ≈ 2 K [2]. However, quantum limited amplifiers for angular frequencies ω lower than 2π×100 GHz should satisfied hard condition $T_N < \hbar\omega \approx 1$ K, where ħ is Planck constant. It was shown, that parametric amplifier based on superconducting coplanar waveguide resonator could satisfy this condition [1]. To create a parametric amplifier from a resonator, some kind of a nonlinear element has to be integrated within. Recently, there have been proposed several types of a parametric amplifier based on a different type of nonlinearity, e.g. kinetic inductance of superconductor [1, 4], nonlinear superconducting weak link [5], Josephson junctions or DC Squid [6]. In this paper, we present parametric amplifier based on a nonlinearity of a pair of superconducting flux qubits composing an elementary unit which can be easily extended to one-dimensional array. Such array can be considered as a quantum metamaterial with large Kerr nonlinearity.

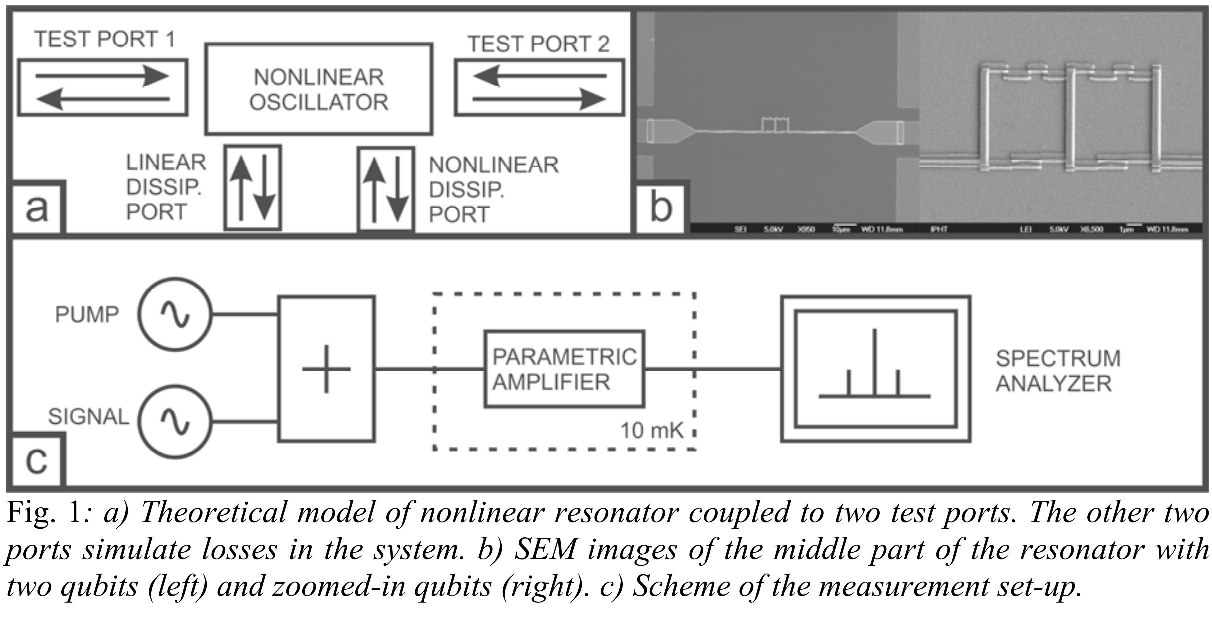

Fig. 1*: a) Theoretical model of nonlinear resonator coupled to two test ports. The other two ports simulate losses in the system. b) SEM images of the middle part of the resonator with two qubits (left) and zoomed-in qubits (right). c) Scheme of the measurement set-up.*

2. Theory

Our system can be described by Hamiltonian of a nonlinear oscillator [7]:

$$H = \hbar\omega_0 AA^+ + \frac{\hbar}{2} KAAA^+A^+ \tag{1}$$

, where A and A^+ are the creation and the annihilation operators of photons in the oscillator, respectively, K is the Kerr constant, which is a measure of nonlinearity in the system. Interactions with our measurement apparatus and environment are modelled by the test and the dissipative ports as shown in fig.1a (See reference [7] and references therein).

Parametric amplification is achieved by strong pumping of the resonator with frequency $\omega_p/2\pi$. The pump frequency is mixed with a weak signal of frequency $\omega_s/2\pi$ by a nonlinear element producing additional signals with angular frequencies ω_s and $2\omega_p - \omega_s$ (idler signal). In other words, two photons from the pump with angular frequency ω_p transform into two photons with angular frequencies ω_s and $2\omega_p$-ω_s, while the energy is conserved.

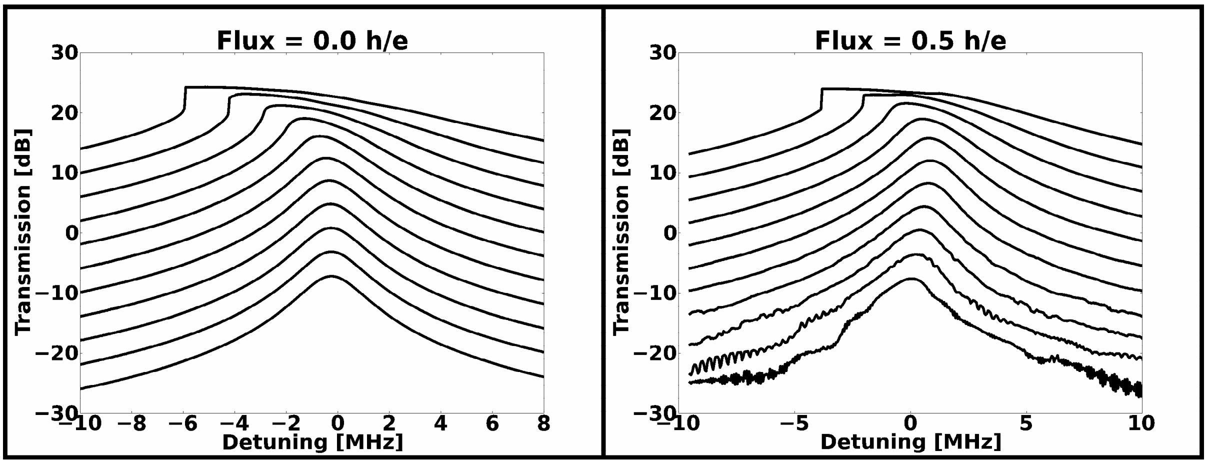

Fig. 2*: Transmission of the resonator in the vicinity of resonance frequency of its third harmonic (7.45 GHz) measured at the magnetic flux Φ=0 (left panel) and $\Phi=\Phi_0/2$ (right panel). Curves, from bottom to top, correspond to input power -90, -86, -82,...dBm. The curves are offset by 4 dB for clarity.*

3. Design and fabrication

The niobium resonator (except the qubit structures) has been prepared by e-beam lithography and dry etching of 200 nm thick film on a silicon substrate. The aluminium qubit structures in the middle of the resonator have been prepared by shadow evaporation technique (fig.1b).

To assure strong coupling between the resonator and the qubits (each of the qubits consists of 5 Josephson junctions), one of the Josephson junctions of each qubit is integrated within the centre line of our resonator.

The resonator is designed to work in an overcoupled regime in order to increase a bandwidth of the parametric amplifier.

4. Measurement set-up

Gain of our parametric amplifier [10] was investigated according to a schematic shown in fig.1c. We kept the amplitude of the signal constant and much lower than the amplitude of the pump, while sweeping the amplitude and frequency of the pump. The frequency difference between the signal and the pump was fixed to 10 kHz (approx. 1% of a bandwidth of our resonator). The magnetic flux in the qubits was set by a biasing coil integrated into the sample holder. The measurement was carried out in a dilution refrigerator with base temperature of 10 mK.

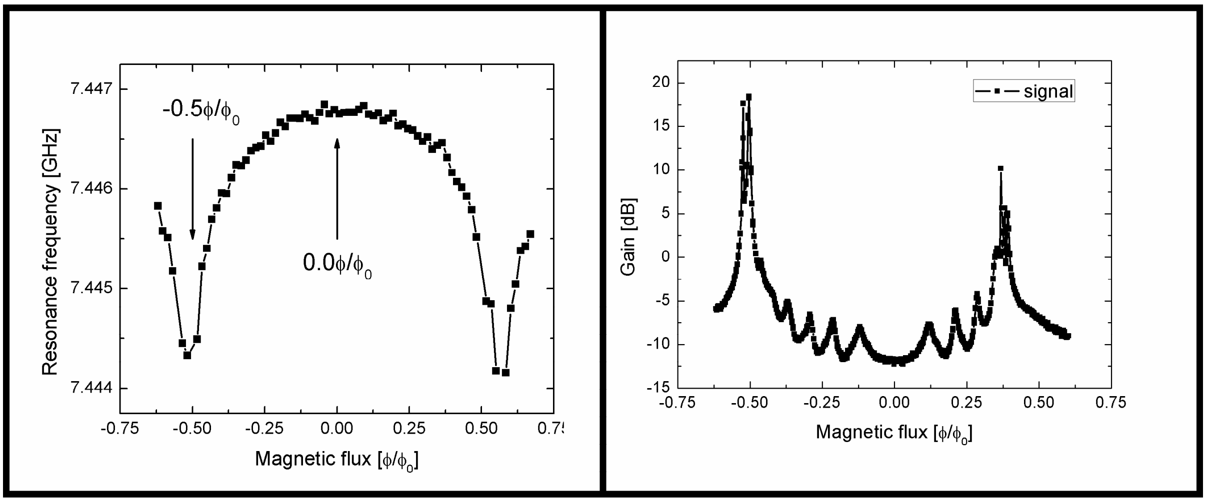

Fig. 3*: Left panel: Detuning of the resonance frequency of the resonator as a function of the applied magnetic flux (several points in an anti-crossing region were omitted). Right panel: Gain of the parametric amplifier as a function of the magnetic flux.*

5. Results and discussion

Before the gain measurements, we characterized properties of our resonator. The transmission of the resonator for different input power exhibits typical behavior of Duffing oscillator [8] (fig.2.). From low input power spectra, we are able to extract the resonance frequency of second excited mode and its loaded quality factor, which we estimated to be: $f_3 = 7.45$ GHz and Q = 4000, respectively.

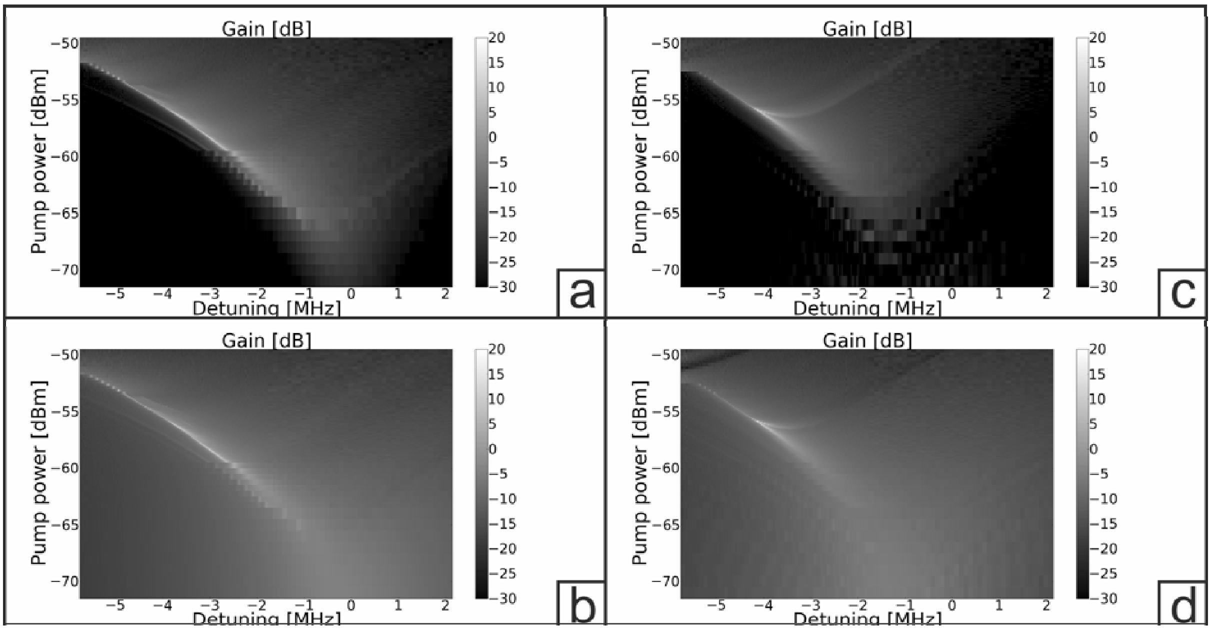

Fig. 4*: Gain of the parametric amplifier as a function of detuning from the resonance frequency (x-axis) and the input pump power (y-axis). a) and c) are images of idler gain; b) and d) are signal gains. a) and b) are measured when magnetic flux $\Phi=0$; c) and d) when $\Phi=\Phi_0/2$.*

We investigated detuning of the resonance frequency in different magnetic fields (fig.3). We chose two working points: magnetic flux $\Phi = 0$ and $\Phi = \Phi_0/2$ (qubit is tuned to resonance with microwave resonator - qubit “anticrossing” [9]), where Φ_0 is a magnetic flux quantum.

The gain of the parametric amplifier depends on the frequency and the power of the pump (fig.4). The magnetic flux in qubits only slightly alters the resulting gain of both the signal and the idler, while the maximal gain is ≈ 18 dB. The main difference between these two cases is a presence of two “high amplification branches” at $\Phi = \Phi_0/2$ instead of one present at $\Phi = 0$. This peculiarity can be a consequence of “Landau - Zenner beam splitting” at qubit anticrossing point [3]. More detailed theoretical quantum analysis of parametric amplification is required in order to clarify this effect.

In order to find the highest gain depending on the magnetic flux, we fixed both the power and the frequency of the signal and the pump at the point where the gain was the highest. The magnetic flux was swept in order to obtain dependence of the gain on the magnetic flux. The highest achievable gain is still 18 dB (fig. 3). Moreover, there is a periodical pattern which is currently unexplained and is object of the analysis.

6. Summary

In summary, we designed a parametric amplifier based on a superconducting coplanar waveguide resonator with a pair of integrated qubits which served as a source of nonlinearity. Our amplifier achieves maximal gain of 18 dB, which is a comparable to the gain of similar superconducting parametric amplifiers [1, 4-6]. However, the experiments reveal two unknown features, namely two “branches” of high amplification in case of bias flux $\Phi = \Phi_0/2$ and a periodical pattern of the gain depending on the bias flux which can be a consequence of a quantum nature of a superconducting qubit. “Landau-Zenner beam splitting” could be a crucial effect responsible for these peculiarities. We are going to investigate these quantum phenomena and complete the characterization of our amplifier by measuring its noise properties.

Acknowledgement

The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under Grant No. 270843 (iQIT). This work was also supported by the Slovak Research and Development Agency under the contract APVV-0515-10 (former projects No. VVCE-0058-07, APVV-0432-07) and LPP-0159-09. The authors gratefully acknowledge the financial support of the EU through the ERDF OP R&D, Project CE QUTE & metaQUTE, ITMS: 24240120032 and CE SAS QUTE.

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[10] Gain of the signal is defined as $20\log(V_{out}(\text{signal})/V_{in}(\text{signal}))$ and gain of the idler as $20\log(V_{out}(\text{idler})/V_{in}(\text{signal}))$.