MACH–ZEHNDER INTERFEROMETRY IN AN ARTIFICIAL QUANTUM TWO LEVEL SYSTEM

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1. Introduction

Superconducting flux qubits are solid-state electrical circuits constituting tunable artificial atoms. A simple flux qubit consists of a micrometer sized superconducting loop interrupted by a several Josephson junctions [1]. The external tuning parameter is the magnetic flux Φ in the loop. The ground and excited states,$|e\rangle$ and $|g\rangle$ of this system are symmetric and antisymmetric superposition of classical states $|0\rangle$ and $|1\rangle$ defined by the direction of the circulating persistent current $I_p$in the loop. At the degeneracy point of the classical states, were the magnetic flux is tuned to half of the magnetic flux quantum Φ_0 (fig. 1a), the degeneracy is lifted because of quantum tunneling, represented by off diagonal Hamiltonian matrix elements

$$H = -\frac{1}{2}\varepsilon\sigma_z - \frac{1}{2}\Delta\sigma_x, \qquad (1)$$

hereΔ is the tunneling amplitude, σ_x and σ_z are Pauli matrices and ε is the energy bias $\varepsilon = 2I_p(\Phi - \Phi_0/2)$ defined by the magnetic flux Φ, I_p is the persistent current. Therefore the ground and exited states of the qubit exhibit an avoided level crossing (fig. 1a).

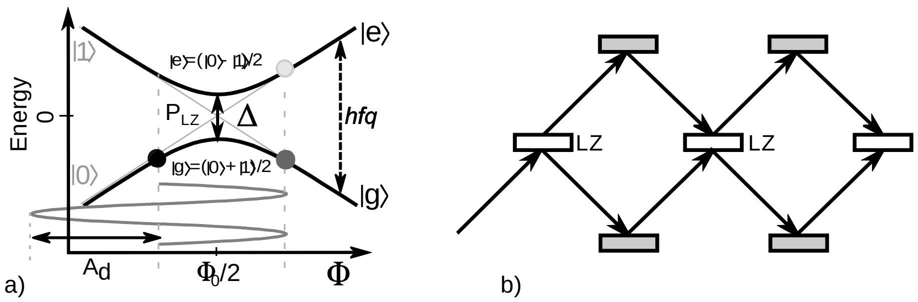

Fig.1: *a) Energy level diagram of a qubit with an avoided level crossing at* $\Phi=\Phi_0/2$. *b) Schematics of optical Mach-Zehnder interferometry,where interference of optical signal is created by beam splitters.*

Rapid sweeping of the magnetic flux at the avoided crossing leads to interesting quantum interference. There are two paths which particle, marked by dark circle, can follow. The first one is adiabatic, following the ground level and the second one follows classical path marked by grey lines in Fig. 1a. Quantum mechanically, the latter can be understood as tunneling from ground state g to excited state e across energy gap Δ known as Landau-Zener tunneling [2,3,4]. Therefore, the avoided crossing acts as a coherent beam splitter. Driving the qubit with harmonic excitation with amplitude A_d and frequency $f_{d,}$, the qubit is periodically swept through the avoided level crossing and splitting the wave function.

Interference of split wave functions, known as Landau−Zener−Stuckelberg (LZS) interference, causes increased population of the excited state of the qubit at resonant condition $n.h.f_d=h.f_q(\Phi)$, where h is the Planck constant, f_q is the qubit Rabi frequency given by the energy level separation and n is an integer corresponding to the order of the photon process [5,6]. Such interference is an analogue of the optical Mach−Zehnder interferometry (fig. 1b), where two beam splitters are used to create interference of optical signal [7,8].The analogy with optics can be pushed even further by coupling a superconducting coplanar waveguide resonator´s photon field to a superconducting qubit [9,10]. In such systems, a population inversion of qubit states can be achieved which can lead to lasing [11,12].

In this paper we report an experimental evidence of a LZS interference in a superconducting flux qubit coupled to a superconducting resonator.

2. Design and fabrication

Two superconducting flux qubits were integrated in the middle of a niobium resonator within the centre line. The resonator was prepared by e-beam lithography and dry etching of 200 nm thick film on a silicon substrate. In the ground plane of the resonator, close to the qubits, an additional excitation loop was design for high frequency high power excitation of the qubits. The resonator was design to work in overcoupled regime, to ensure sufficiently high transmission. The fundamental resonance frequency and quality factor of the resonator were designed to 2.5GHz and 10 000, respectively. The aluminum qubits were prepared by shadow evaporation technique (fig.1b). Each qubit, a superconducting loop interrupted by 5 Josephson junctions, is strongly coupled to the resonator by a shared Josephson junction.

3. Experimental set-up

The experiment was carried out in a cryogenic-free dilution refrigerator with base temperature of 10 mK. The sample was glued and wire-bonded to a printed circuit board with 50μm aluminum wires and enclosed in a copper box. On the input line, where a weak probing signal at frequency f_s was applied (VNA N5242A), a set of thermally anchored attenuators were placed. On the output line, a cryogenic circulator was installed between a sample and theSiGe cryogenic amplifier placed on 3 K plate in order to isolate the sample from the thermal noise (Fig. 2a).

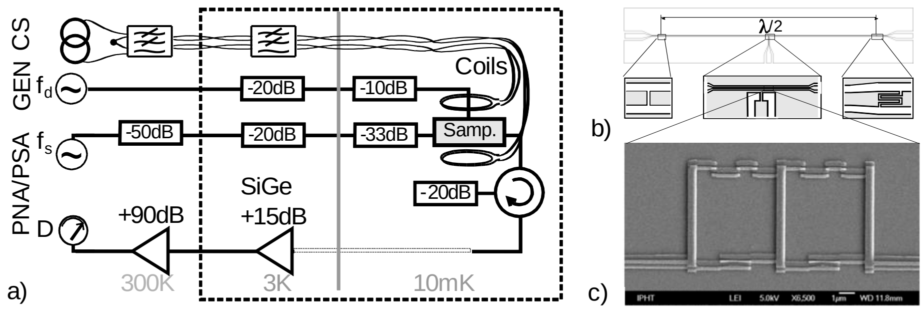

Fig.2: *a) Scheme of the rf- experimental set-up in the refrigerator. b) Scheme of the niobium resonator and the detail of the excitation loop. c) SEM image of the aluminiumqubits in the resonator.*

The output signal was further amplified by five room temperature amplifiers and the signal was detected by vector network analyzer (VNA N5242A, homodyne detection). In order to be able to drive the qubit strongly at frequency f_d (GEN E8257D PSG) an additional excitation line was utilized with considerable smaller total attenuation. The qubit was biased by dc magnetic field provided by two superconducting Helmholtz coils. Coils were fed by dc current filtered by a carbon powder filter placed at 3K plate.

4. Results

The fundamental frequency f_0~2.481GHzand quality factor of the resonator was measured by network analyzer to Q~9800. Both, the dispersive resonance frequency shift of the resonator and the spectroscopic measurement of the sample shows that the sample behaves effectively as a single qubit.

A strong harmonic drive of the qubit−resonator system at frequency $f_d=3f_0$ leads to an increase of both the transmission coefficient and the quality factor of the resonator at resonant condition $n.h.f_d=h.f_q(\Phi)$. The transmission of the resonator is strongly enhanced or depressed periodically, depending on both the amplitude of the applied driving signal $A_d$and external magnetic flux. The dependence of the resonator's transmission on the magnetic flux Φ and the amplitude of the driving field A_d reveals a interference pattern up to 8 photon resonances and 4 interference fringes. We explain the periodic structure of the resonator's transmission by LZS interference. From the arc around the point $A_d=\varepsilon=0$ in fig. 3 we expect the driving of the qubit across the avoided level crossing to be close to the slow-driving limit $A_d\omega<\Delta^2$. In the slow-driving limit the average occupation probability of the qubit's excited state is

$$P_+ = \frac{P_{LZ}(1+\cos\zeta_+\cos\zeta_-)}{\sin^2\zeta_+ + 2P_{LZ}(1+\cos\zeta_+\cos\zeta_-)}, \qquad (2)$$

where $\zeta_+(\zeta_-)$ is the sum (difference) of the qubits state vector's phases acquired during the adiabatic driving between subsequent crossings of the degeneracy point. For more details please see [6]. The numerically calculated average occupation probability for qubit parametersI_p~21 nA, Δ~2.35 GHz and driving frequency 7.5 GHz is shown in fig. 4. The presented numerical calculation resembles the measured interference pattern, however for detailed analysis the qubits relaxation and dephasing time and the resonator-qubit interaction has to be taken into account.

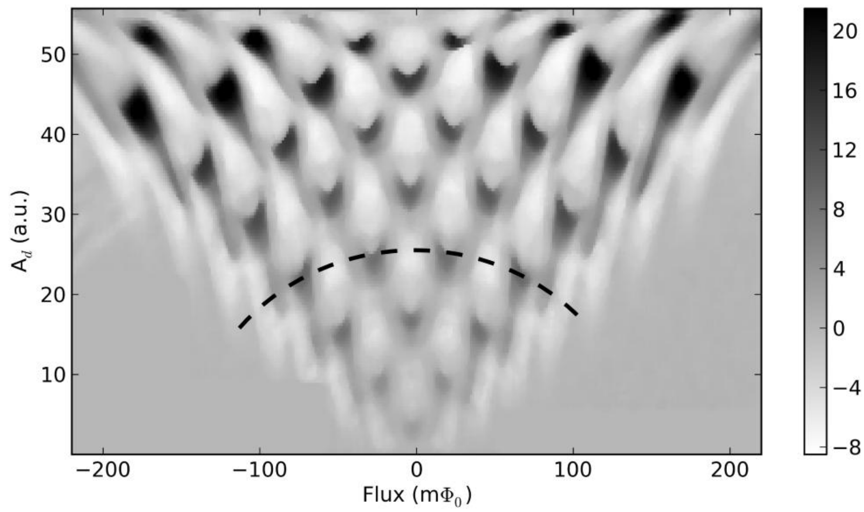

Fig.3: *The dependence of the resonator's normalized transmission (homodyne measurement, input power p_s~−140dBm) on the magnetic flux $\delta\Phi=\Phi-\Phi_0/2$ and the amplitude of the driving field A_d. LZS interference pattern is visible up to 8 photon resonances and 4 interference fringes.*

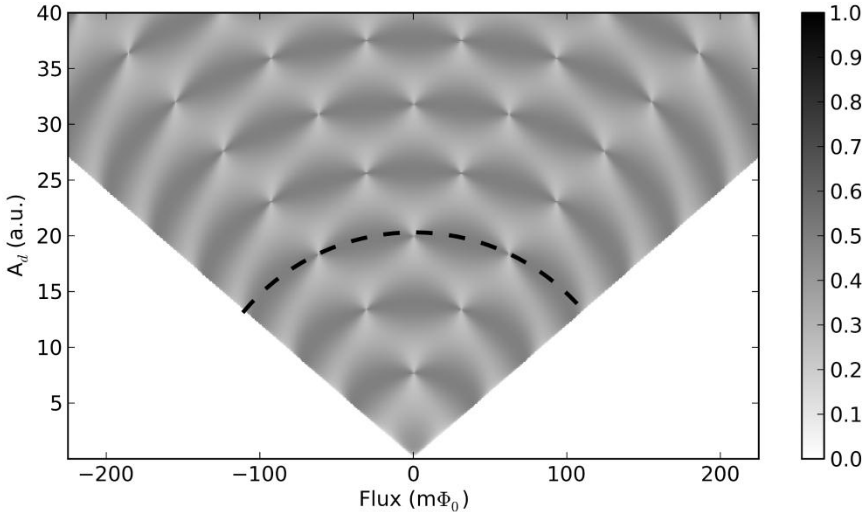

Fig.4*: Average occupation probability of the qubit's excited state on dependence of the on the magnetic flux $\delta\Phi=\Phi-\Phi_0/2$ and the amplitude of the driving field A_d in slow-driving limit $A_d\omega \lesssim \Delta^2$ for qubit parameters is I_p~21 nA, Δ~2.35 GHz and driving frequency 7.5 GHz.*

5. Conclusion

LZS interference on a flux qubit in circuit QED experiment was experimentally demonstrated. The strong driving of the qubit could lead to population inversion and to lasing. The work is in progress.

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References:

[1] J. E. Mooij et al., Science, **285**, 1036 (1999)
[2] L. Landau, Phys. Z. Sowjetunion **2**, 46 (1932)
[3] J. R. Rubbmark et al., Phys. Rev. A **23**, 6 (1981)
[4]A. Izmalkov et al.,Europhys. Lett. **65**, 844 (2004)
[5] A. Izmalkov et al., Phys. Rev. Lett. **101**, 017003 (2008)
[6] S.N. Shevchenko et al., Phys. Rept. **492**, 1 (2010)
[7]A. V. Shytov et al., Eur. Phys. J. B **36**, 263 (2003)
[8] W. D. Oliver et al., Science **310**, 1653 (2005)
[9] A. Blais et al., Phys. Rev. A **69**, 062320 (2004)
[10] A. Wallraff et al., Nature **431**, 162 (2004)
[11] O. Astafiev et al., Nature **449**, 588-590 (2007)
[12] G. Oelsner et al., Phys. Rev. Lett**110**, 053602 (2013)