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HIGH-QUALITY RESONATORS FOR QUANTUM INFORMATION SYSTEMS

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Abstract

We analyze ultra-high-quality factor resonators for quantum computer architectures. As qubit operation requires external DC fields, we started our study with a conventional closed copper cavity, which naturally allows external magnetic fields. In order to increase quality factor and to keep DC magnetic field control at a level less than critical field, an open SRF resonator promises much higher quality. The next step resonator is a photonic band gap (PBG) resonator. This resonator allows easy external control for either magnetic or electric field. It consists of a periodic 3D set of sapphire rods assembled between two superconducting plates. The PBG resonator exploits unique properties of the crystalline sapphire. Tangent delta for sapphire in X-band is reported at 10^{-9} - 10^{-10} at 4 K. That is why, the Q-factor of the sapphire PBG resonator can be expected as high as 10 billion at mK temperatures which provides long relaxation times (dephasing etc.). The established PBG design implies obtaining a large Purcell factor, i.e. large ratio of quality to mode volume which is an important parameter to establish strong interaction of a qubit with the cavity mode, rather than RF noise.

INTRODUCTION

Quantum computing is one of the most ambitious goals in modern physics [1]. Many developed concepts of quantum computer architectures imply interaction of qubits with microwave photons. These concepts require high-quality (SRF) resonators [2-5]. A more particular requirement is an opportunity to provide an efficient qubit control, which includes RF field control and DC field control as well. In this paper, we describe two ideas for X-band resonators to be used in Quantum Information Systems (QIS). The first idea involves a normal conducting copper resonator with tunable couplers to be operated at cryogenic temperatures, the second one is a PBG sapphire resonator with SRF end cups.

A COPPER RESONATOR FOR MEISSNER TRANSMON QUBIT

The resonator functions at the TM_{110} mode and has a thin hole in the center for qubit installation (Fig. 1). This resonator design includes two coaxial couplers with tuning bolts, in order to vary the external Q-factor. Figure 2 shows the eigen mode field structure. The couplers have SMA connectors in each of their ends (Fig. 3). In Fig. 4 one can see a photograph of the tested resonator. This resonator was designed for a frequency 8 GHz, so that the intrinsic quality, Q_0, equals 3×10^4 (OFHC cavity, RRR=300, T= 4.2°K).

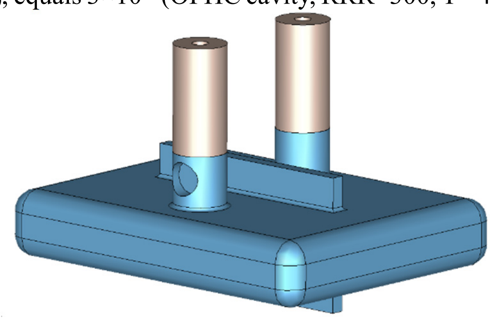

Figure 1: X-band copper resonator for Meissner qubit.

In Table 1, one can see the key parameters and dimensions of the resonator. The external Q-factor could be tuned in a broad band. The mentioned flexibility in tuning range allowed for the testing of various qubits with different sizes, eigen frequencies and insertion losses. The resonator was tested at room temperature, the measured characteristics were in good agreement with calculated ones.

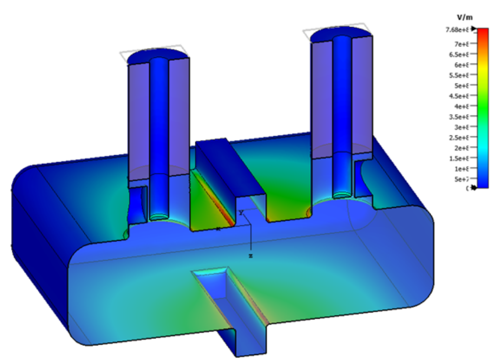

Figure 2: Surface electric field of the eigen mode.

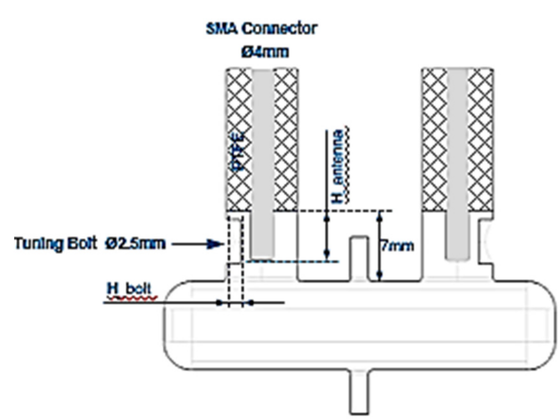

Figure 3: Drawing of X-band copper cavity.

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Table 1: Parameters of the X-band Copper Cavity for Cryogenic Temperature Regime

Parameter	Value
Frequency	7.948 GHz
Cavity size	24×7×28 mm^3
Slot size	2×11×18 mm^3
Q_0	31650
Q_{ext}	18000-37000

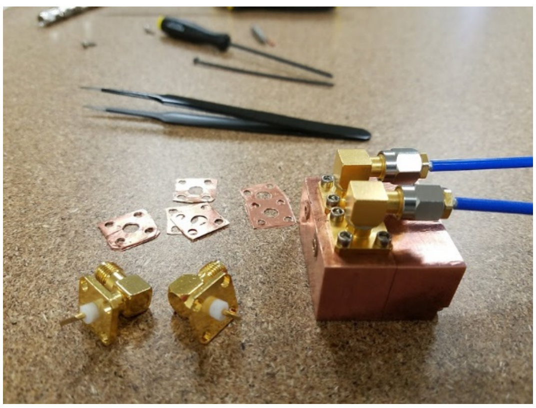

Figure 4: Photograph of the tested resonator.

A PBG SAPPHIRE RESONATOR

Unique properties of ultrapure sapphire at cryogenic temperatures have been reported in many publications [6, 7]. It was confirmed that loss tangent drops with decreasing temperature and in S-band is as low as 10^{-10} (Fig. 5). This incredibly low absorption inspired investigations to implement this material in SRF Nb cavities, even at a high-power level (~20 Mv/m), which is typical for particle accelerators [6].

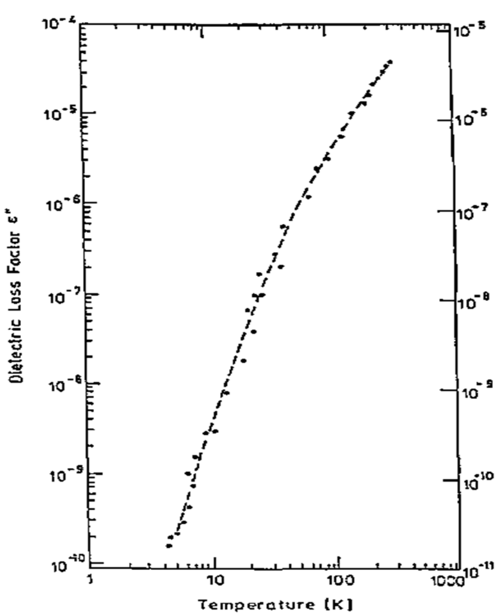

Figure 5: Dielectric loss factor and tangent delta of sapphire at 2.45 GHz vs temperature [7].

Quantum information systems work at extremely low temperatures (~mK level) and at low RF power level. Both peculiarities make the use of a sapphire material appealing. We propose to build Photonic Band Gap (PBG) resonators. The conceptual design of PBG sapphire resonator for QIS is shown in Fig. 6. Here sapphire rods are shown in green. The high-quality resonator is shaped by a periodic grid of sapphire rods, end cups are assumed to be made of superconducting Niobium. This resonator allows easy control of either the external magnetic or electric field. Input/output couplers are based on conventional SMA connectors. The eigen mode has the only longitudinal component of the electric field without variations on the longitudinal coordinate. The transverse field structure depends on the reflectivity of Bragg side reflectors. The larger the reflectivity the more the eigen mode field is localized near the resonator's center.

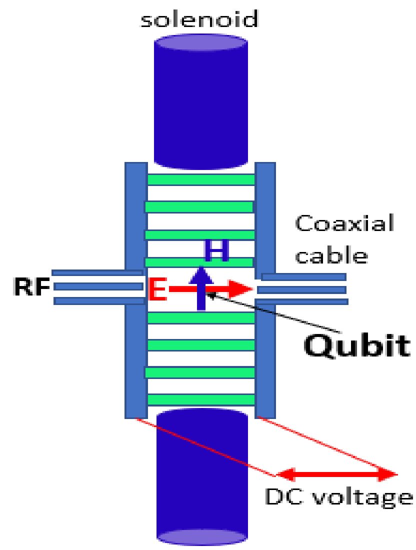

Figure 6: Sketch of sapphire resonator with SRF walls and DC electric or magnetic bias.

Let us consider Bragg reflector properties in more detail. The scheme of the 2D Bragg reflector consists of sapphire rods and irradiated by plane wave is shown in Fig. 7. The electric field is assumed to be parallel to the rods. We optimized period of the grating as well as the rod's diameter, in order to obtain maximum reflection. The optimized parameters are shown in the Table 2. Figure 8 represents the transmission and reflection plot for N=8 number of rod layers. The plot of transmission at the frequency corresponding to the exact Bragg resonance is shown in Fig. 9. This figure shows that transmission exponentially decreases when number of the layers increases.

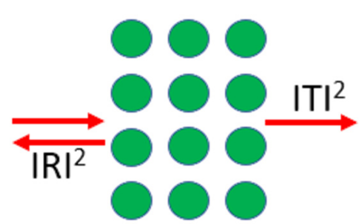

Figure 7: 2D Bragg reflector.

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Table 2: Parameters of Sapphire Bragg Reflector

Parameter	Value
Central frequency	10 GHz
Dielectric permittivity	10
tanδ	10^{-10}
Period	9.55 mm
Diameter of rods	4.9 mm

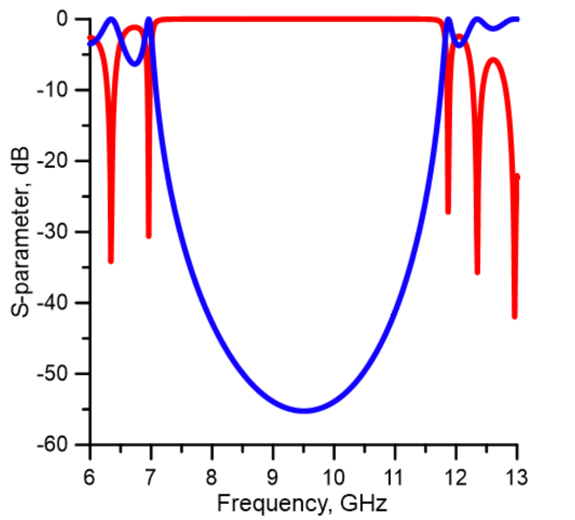

Figure 8: Reflection (red curve) and transmission (blue) characteristics of Bragg reflector vs frequency for N=8 layers.

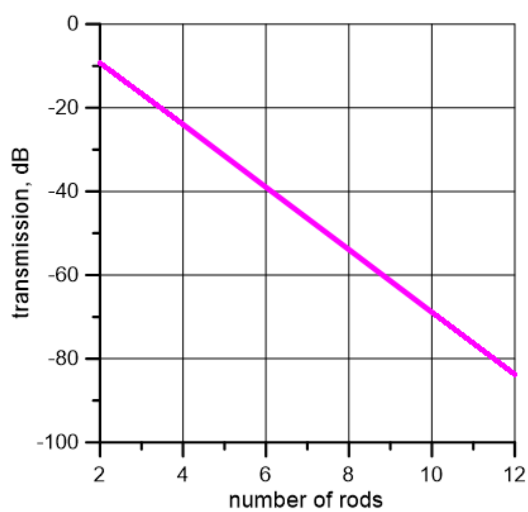

Figure 9: Transmission through Bragg reflector at central frequency of Bragg resonance vs number of rods.

Figure 10 represents the eigen mode field structure in the resonator consisting of only four layers of the sapphire rods. The eigen mode is strongly localized at the center, where one rod was removed from the perfectly periodic grating. In simulation, we set the radiation boundary conditions at the external resonator boundaries. At the resonant frequency of 10 GHz, the eigen mode had a Q-factor of $6{\times}10^3$, which included absorption in addition to leakage losses. For the resonator consisting of 8 layers, the Q-factor reached 10^7, and in the resonator consisting of 12 layers (Fig. 11), Q-factor reached as high as 10^{10}, corresponding to the typical quality of Nb SRF resonators. Note that the chosen PBG design implies obtaining a large Purcell factor, i.e. large ratio of quality to mode volume. The proposed design allows for a natural scaling of architecture toward multi-qubit systems.

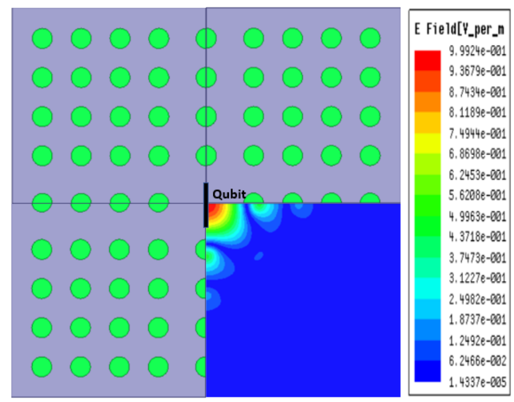

Figure 10: Structure and E-field distribution (linear scale) of operating eigen mode in resonator consisted of 4 layers of rods.

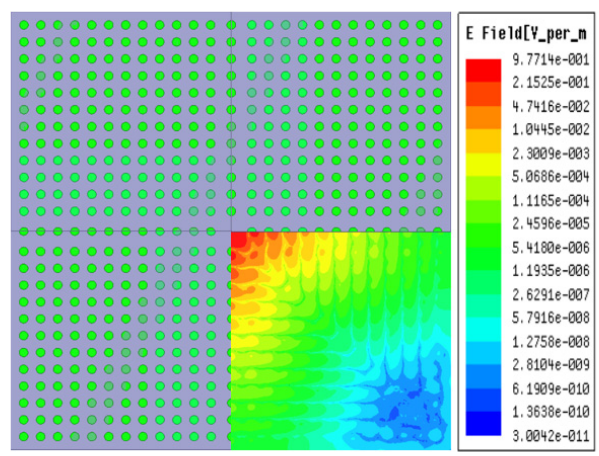

Figure 11: Structure and E-field distribution (logarithmic scale) of operating eigen mode in resonator consisted of 12 layers of rods.

CONCLUSION

SRF sapphire resonators can provide efficient control of a qubit through external DC electric or magnetic fields. Q-factors can be comparable with those of metallic SRF resonators.

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