Incorporation of a dc bias in a high-Q 3d microwave cavity

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We report a technique for applying a dc bias in a 3d microwave cavity. This is achieved by isolating the two halves of the cavity with a dielectric and directly using them as dc electrodes. By embedding a variable capacitance diode in the cavity, we tune the resonant frequency with a dc voltage at room temperature, demonstrating the introduction of a dc bias into the 3d cavity without compromising its high quality factor.
In recent years, interest in 3d waveguide cavity resonators has been revived in the josephson junction quantum bit (qubit) community.\textsuperscript{1−10} Significantly enhanced relaxation times $T_1$ and $T_2$ on the order of tens of microseconds have been demonstrated.\textsuperscript{1,2} Since then, the 3d architecture has also enabled the measurement of entangled qubits\textsuperscript{4,9}, single-photon Kerr effect\textsuperscript{6} as well as the Autler-Townes effect.\textsuperscript{8} So far, these results are achieved without the need of a dc bias. However, the ability to do so will significantly expand the application of the 3d cavities, just as the introduction of a dc bias into a coplanar waveguide cavity made it much more versatile.\textsuperscript{11} For example, this would enable the actuation of a nanomechanical resonator, making optomechanics feasible in 3d cavities. For qubit measurements, flux bias can be added by applying a dc current bias.

The dimensions of our near-rectangular cavity are illustrated in Fig. 1(a). The rounded corners in the xy-plane have a radius of 3 mm. The resonant frequency of the lowest TE101 mode is expected to be around 7.705 GHz according to a Comsol simulation shown in Fig. 1(b). The color corresponds to the magnitude of the electric field in the zx-plane, at the center of which the field reaches maximum. The cavity is constructed by attaching two aluminum blocks, each embedding one half of the cavity to each other. An SMA connector is secured on one of them for reflective measurement. The resonant frequency of the bare cavity at room temperature and in the atmosphere is measured to be $f_0 = 7.743$ GHz, indicated by the cavity response plotted in Fig. 1(c). The cavity is connected via an input capacitance $C_{in}$ to a vector network analyzer (VNA) of characteristic impedance $Z_c = 50$ Ω. The characteristic impedance of the cavity is $Z_{TE10} \approx 540$ Ω. Following the method described in Ref. 12, the loaded, intrinsic and external Q-factors $Q_L$, $Q_0$ and $Q_e$, as well as $C_{in}$ can be extracted respectively. The loaded Q-factor in this setting is about $Q_L = 3920$.

A loss channel for the cavity photons is inevitably introduced when a dc bias line is added into the 3d cavity. The existing scheme for dc bias in a rectangular waveguide typically requires extra slots guiding the bias lines from the free space into the cavity and additional lumped-element low-pass filters to prevent the microwave fields from leaking out of the cavity, (see for example Ref. 13 and 14) adding to the complexity and challenges of device fabrication. Firstly, the loss associated with each component has to be extremely low in order to preserve the high quality factor of the cavity. Secondly, the lines to the filter
can potentially cause common mode problems since the electrical ground start to float at high frequencies. Extra power radiates, spoiling the Q-factor. Our technique solves these problems by separating the two hemispheres of the cavity with a thin layer of insulator and using them directly as electrodes. The interface of the two halves forms a large capacitor, ideal for a low-pass filter. We directly apply the dc voltage on the aluminum blocks, which provide highly effective grounding for microwaves. The need for extra slots and filters is therefore eliminated. Using superconducting wires from the two halves of the cavity to devices embedded in it, such as qubits, one can then apply voltage or current biases to the devices. This could even be implemented with traces directly on the sapphire substrates used to hold the devices in the cavity. The bandwidth of this dc bias scheme is limited by the capacitance between the two hemispheres and can be carefully engineered. For a 50 Ω coax cable and a 400 pF capacitor the bandwidth is estimated to be around 8 MHz. One can also transform the cable impedance to achieve higher bandwidths.

To understand the limitations on the quality factor of such split cavities, we consider possible loss mechanisms. In particular, two candidates could be the dielectric loss and the radiation loss. Experimentally, we estimate the extra loss in the cavity by comparing the Q factors of the split and non-split cavities. At room temperature, for PTFE film (0.1 mm thick) the intrinsic decay rate \( \gamma_0 = f_0/Q_0 \) typically increases by \( \Delta \gamma_0 \approx 5 \text{ kHz (0.28\%)} \) compared to the bare cavity, corresponding to a limitation on the Q factor of \( 1.5 \times 10^6 \). The quality factor \( Q_L \) of a 3d cavity operating at low temperature is usually on the order of \( 10^5 \) and the contribution of \( \Delta \gamma_0 \) can be disregarded.

To demonstrate this method we embed a diode inside the cavity. Its capacitance is modulated by a reverse voltage bias and the cavity resonant frequency is subsequently shifted. As shown in Fig. 2(a), the interface of the left and right halves are separated by a thin layer of insulator indicated by the blue shades. Inside, the anode (cathode) of the diode is attached to the left (right) half of the cavity. An external dc voltage source is attached to the aluminum blocks, reverse-biasing the diode via the cavity walls. One half of the actual cavity is shown in Fig. 2(b). The interface is sealed with a layer of office tape (0.05 mm thickness) and nylon screws are used to connect the two halves of the cavity. An equivalent parallel circuit model is illustrated in Fig. 2(c), in which the resistance \( R \), the inductance \( L \)
and the capacitance $C$ model the basic resonance while the capacitance of the diode $C_d$ is coupled to the circuit via a coupling capacitor $C_c$.

We perform an $S_{11}$ measurement with an input power of 0 dBm. As shown in Fig. 3(a), where we plot the reflection coefficient $\Gamma$ as a function of the frequency $f$. The resonant frequency $f_0$ shifts to higher values as we increase the reverse bias voltage $V$ applied on the diode. The quality factors of the cavity show no signs of decrease for $V$ as high as 30 V. The loaded quality factor is $Q_L \approx 2084$ at 0 V and $Q_L \approx 2292$ at 30 V. From the circuit diagram in Fig. 2(c) we can derive $\omega_0^2 = \frac{1}{L(C+(1/C_c+1/C_d)^{-1})}$, where $\omega_0 = 2\pi f_0$. Assuming $C_d \gg C_c$, rewriting $1/\omega_0^2$ as $y$ and $1/C_d$ as $x$, the above equation can be rearranged into a linear equation $y = L(C+C_c) - LC_c^2x$. Using the value of $C_d$ corresponding to each $V$ provided by the diode data sheet, we plot $1/f_0^2$ as a function of $1/C_d$ and perform a linear fit as shown in Fig. 3(b). We further approximate the value of the characteristic impedance $Z_0 = \sqrt{L/C}$ to be $Z_{TE10} \approx 540 \, \Omega$, and obtain the following parameters: $L \approx 10 \, \text{nH}$, $C \approx 35 \, \text{fF}$, $C_c \approx 6.65 \, \text{fF}$.

In conclusion, we have demonstrated a simple method of applying a dc bias up to 30 V in a 3d microwave cavity that does not deteriorate the Q-factor. Using superconducting materials at low temperature, the performance of the cavity can be further optimized.

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FIG. 1. (a) Design of the 3d cavity. (b) Electric field magnitude of TE101 mode modeled by Comsol. (c) Reflection coefficient of the bare cavity (red curve) with a Lorentzian fit (blue curve). The cavity is undercoupled and the quality factors $Q_0 = 4275$ and $Q_e = 47285$ can be extracted. Inset: the cavity is connected to the VNA via an input capacitance $C_{in} \approx 0.6 \text{ fF}$.

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FIG. 2. (a) Schematic of the experimental set-up. The diode inside the cavity is reverse-biased by an external voltage applied across the cavity and the resonant frequency is measured reflectively. (b) A photograph of one half of the aluminum cavity. (c) An equivalent circuit diagram. The tunable diode capacitance $C_d$ is coupled in parallel to the main cavity through $C_c$.

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FIG. 3. (a) Representative $S_{11}$ curves measured by the VNA as the bias voltage $V$ is varied. The resonance frequency is shifted but the quality factor preserves. (b) Inverse square of the resonant frequency as a function of the inverse of the diode capacitance.