Snowmass2021 - Letter of Interest

[1]

Tunable Quality Factor Resonators for High Energy Applications

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☑ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☑ (IF01) Quantum Sensors

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Abstract: (maximum 200 words)

Detectors made of superconducting resonators are generally designed as planar devices to reduce the loss due to two-level systems (TLSs). However, these planar devices have large footprints and are still limited by the quality of the materials. We developed a method of controlling TLS populations which allows us to tune the quality factor of resonators from lossy devices through the power balance point, and to a gain regime where they can perform like amplifiers. Our resonator devices use trilayer capacitors, allowing us to continue using conventional CMOS fabrication while reducing the size of the devices. We propose exploring these devices for use as quantum limited amplifiers and as MKIDs for high energy applications.

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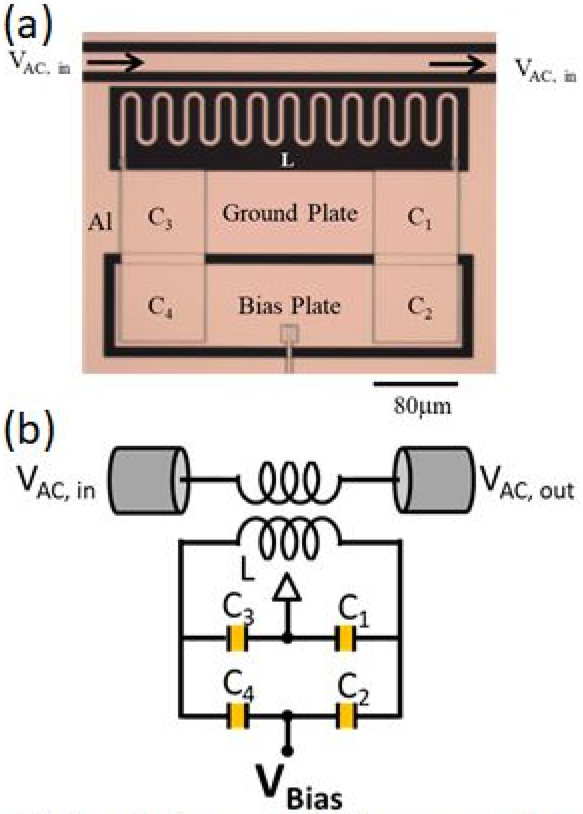
There are a range of cutting-edge superconducting devices of interest to HEP: the Josephson-junction based parametric amplifiers in use by the ADMX and HAYSTAC axion searches; the Josephson junction - based qubits being proposed for future axion searches, and the kinetic inductance detectors (also superconducting resonators) in development for dark matter searches and mm-wave cosmological surveys of the CMB and large-scale structure. Two-level systems (TLS) are a common feature in all these devices, generally considered a nuisance because of their loss and noise.

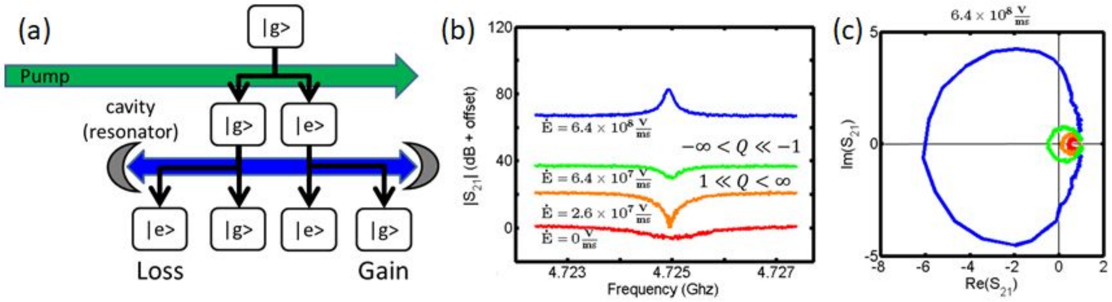


(a) Sample image and (b) corresponding schematic for the bias-bridge resonator. The bias line is decoupled from the transmission line due to symmetry. The bias line contains two RF signals at ±5 MHz from the resonance frequency to pump TLSs with RF energy. It is combined with a ~100 kHz sawtooth sweep which continuously changes TLS energies over a large >1GHz range.

The TLSs consist, generally, of defect states in amorphous materials nearby or incorporated in such devices. The defects can switch between two spatial configurations, like a particle in a quantum-mechanical two-well potential. This results in a ground state and at least one excited state separated by a splitting. These TLSs generally have an electric dipole moment, leading them to exchange energy with nearby RF systems such as those of interest above. They can also lose energy via phonon emission, creating a loss mechanism that can cause decoherence. Any loss comes with associated fluctuations and thus noise.

These two-level systems are thus generally considered a problem to be minimized or worked around. In particular, many such devices have taken to using large, planar, interdigitated capacitors (TLS impact capacitive components where the electric field resides) because the bulk of the field is in the low-defect crystalline substrate, with only thin, parasitic oxide layers nearby. TLSs nevertheless are still present, just reduced in effect. If TLSs could be controlled and their influence nullified, then more compact configurations incorporating bilayer or trilayer capacitors using amorphous dielectrics could be entertained. Furthermore, because of their nonlinear behavior they can be treated as a large natural source of qubits, and control of TLSs can turn them from a deleterious effect into an advantage, with the potential to provide gain.

Previous work [1] has demonstrated operation of a superconducting resonator with tunable quality factor by controlling the populations of TLSs. The device consists of a lumped element resonator with a lossy trilayer capacitor in a bias-bridge configuration. The lumped element nature of the capacitor allows it to take a relatively small footprint on the device, reducing the size with respect to distributed elements. Trilayer capacitors are ideal for other reasons - the dielectric further reduces the device footprint, and localizes the electric fields to reduce crosstalk or coupling to lossy states outside of the device area. However, the bias-bridge configuration is the main advantage in the device. This configuration adds a bias line that allows us to apply an electric field to the TLSs without affecting the resonance mode. A TLS will change its resonance frequency as a function of this bias field.



(a) TLSs begin in the ground state due to the low temperature. A sweeping electric field bias changes their energy towards a pumping field which can invert them. They then reach degeneracy with the resonator and depending on their state, they can cause gain or loss. (b) Magnitude of transmission as a function of frequency and (c) an I-Q plot for a superconducting resonator with TLS population control. The quality factor can be tuned from very low Qs, past infinite Q, and into the gain regime, causing amplification of the signal.

By applying a strong enough pumping field to the dielectric (this can be added to the bias line so there is no signal on the inductor), a continuously varying bias field can induce a STIRAP-like inversion [2,3] in the TLSs. The TLS populations can then be tuned from ground to excited in a small bandwidth around the resonance frequency. It is well known that resonant TLSs are the dominant source of loss when using trilayer capacitors [4]. At these temperatures TLSs are generally in the ground state and can accept energy from the resonator, decreasing quality factors. By inverting the population of the TLSs, those defects become unavailable for energy loss processes and the resonance becomes sharper. As inversion percentage is increased the device can pass the point of energy loss and enter a region of coherent gain due to the TLSs.

We propose using this device to explore high energy applications. One such application is as a quantum limited amplifier. An amplifier with this design will be compact, can be placed on a chip, and when in-plane should be robust against large magnetic fields. The design is repeatable and requires minimal tuning. It could therefore be used in large magnetic field experiments like ADMX to amplify small signals.

Another application that can be explored with this device is MKIDs. The resonator's meander inductor can be fabricated using a high kinetic inductance material. The ability to tune the quality factor can be used to increase the sensitivity to kinetic inductance changes in the inductor. Once a photon is detected, a fast feedback system could also be used in conjunction with the Q tunability to 'reset' the device in preparation for a new photon. With advantages like a small footprint, easy fabrication with dielectrics, and low crosstalk, we propose to explore this device for high energy applications.

References: (hyperlinks welcome)

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