Minimizing quasiparticle generation from stray infrared light in superconducting quantum circuits

R. Barends,[1,a)] J. Wenner,[1] M. Lenander,[1] Y. Chen,[1] R. C. Bialczak,[1] J. Kelly,[1] E. Lucero,[1] P. O'Malley,[1] M. Mariantoni,[1] D. Sank,[1] H. Wang,[1] T. C. White,[1] Y. Yin,[1] J. Zhao,[1] A. N. Cleland,[1] John M. Martinis,[1] and J. J. A. Baselmans[2]
[1]Department of Physics, University of California, Santa Barbara, California 93106, USA
[2]SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

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We find that quasiparticle generation from stray infrared light creates a significant loss mechanism in superconducting resonators and qubits. We show that resonator quality factors and qubit energy relaxation times are limited by a quasiparticle density of approximately 200 μm^{-3}, induced by 4 K blackbody radiation from the environment. We demonstrate how this influence can be fully removed by isolating the devices from the radiative environment using multistage shielding. [doi:10.1063/1.3638063]

Quantum information processing in superconducting circuits is performed at very low temperatures, so energy loss due to quasiparticles is expected to vanish because their density diminishes exponentially with decreasing temperature. As energy relaxation times saturate for superconducting quantum circuits, reaching values on the order of 1-10 μs at the lowest temperatures,[1–4] recent experiments have suggested that this may be due to excess non-equilibrium quasiparticles; measurements on resonator quality factors,[3,4] phase qubit coherence,[5,6] tunneling in charge qubits,[7] and quasiparticle recombination times[8,9] are compatible with an excess quasiparticle density on the order of 10-100 μm^{-3}.

In this letter, we demonstrate that quasiparticle generation from stray infrared light is a significant mechanism for loss and decoherence in resonators and qubits and is a limiting factor in our present resonator experiments. We find resonator quality factors and qubit energy relaxation times consistent with a quasiparticle density of approximately 200 μm^{-3}. We show quantitatively how a combination of shields removes the influence of stray infrared light and that the required shielding is in excess of what is typically used. We dramatically reduce the stray light-induced quasiparticle density to an upper limit of 0.2 μm^{-3} when using a light-tight sample stage and find that our quality factors and energy relaxation times are thereby unaffected by stray light.

The quasiparticle density n_{qp} controls the loss in a superconducting resonator with frequency f_r and quality factor Q,[10,11] (for $kT \ll hf_r$)

$$\frac{1}{Q} = \frac{\alpha}{\pi}\sqrt{\frac{2\Delta}{hf_r}}\frac{n_{qp}}{D(E_F)\Delta}, \quad (1)$$

where Δ is the energy gap, $D(E_F)$ the two-spin density of states, and α the kinetic inductance fraction, which depends on geometry. Importantly, excess quasiparticles appear as an additional loss term.

Quasiparticles are generated by the absorption of infrared light, which can enter the sample mount through the lid joint and connectors. The rate equation for the total number of quasiparticles is[12]

$$\frac{\delta N_{qp}}{\delta t} = \frac{P}{\Delta} + G - RN_{qp}^2, \quad (2)$$

where P is the absorbed power for which $hf > 2\Delta$, G the standard thermal generation term due to pair breaking by phonons,[13] and R a material-dependent recombination constant. Without the P/Δ term, Eq. (2) leads to the standard thermal quasiparticle density given by $n_{qp} = D(E_F)\sqrt{2\pi kT\Delta}\exp(-\Delta/kT)$. Under strong loading, when the light-induced density exceeds the thermal background, the quasiparticle density scales as $n_{qp} \propto \sqrt{P/\Delta}$. Aluminum is particularly sensitive to stray light: the gap frequency is 88 GHz—hence 96% of the power of a 4.2 K blackbody can be absorbed—and quasiparticle recombination is slow.[8,9]

Additional loss due to excess quasiparticles is already visible in the temperature dependence of Al resonator quality factors, as shown in Fig. 1. Here we plot quality factors of coplanar waveguide (CPW) resonators (inset Fig. 1). The open symbols are measured when simply placing the sample in a sample box inside a cryostat, with no special measures to minimize stray light ("typical shielding"). Above a temperature of 200 mK the quality factors decrease

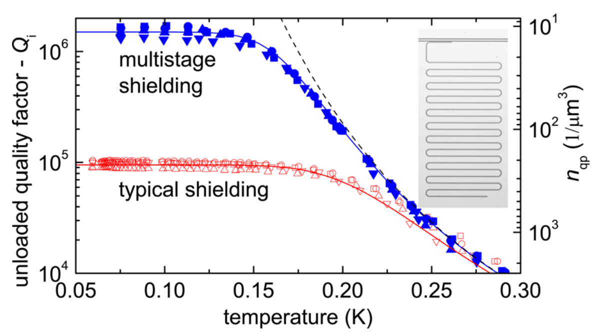

FIG. 1. (Color online) The quality factors of four halfwave coplanar waveguide Al resonators versus sample stage temperature, measured in a setup without effort to shield stray infrared light (open symbols) and with an improved light-tight sample stage (closed symbols). Right axis shows the corresponding quasiparticle density n_{qp}. Resonance frequencies lie between 3.8 and 4.5 GHz. Eq. (1) is plotted for an exponentially decreasing quasiparticle density (dashed line), excess quasiparticle density of 230 μm^{-3} (bottom solid line) and 10 μm^{-3} (top solid line). Kinetic inductance fraction $\alpha = 0.28$ for these devices (Ref. 14). Inset shows a halfwave resonator capacitively coupled to a feedline.

a)Electronic mail: rbarends@physics.ucsb.edu.

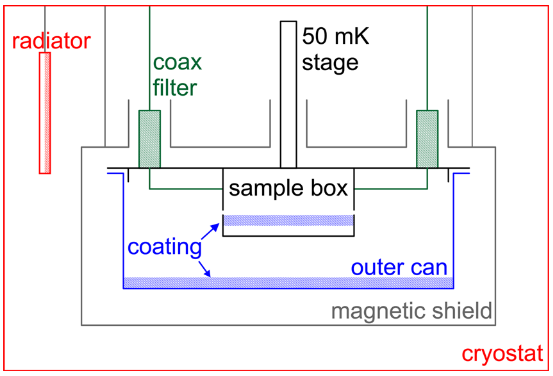

FIG. 2. (Color online) Schematic representation of the light-tight sample stage: the sample box is mounted inside a larger box on the 50 mK stage, closed off by an outer can. The inner surfaces of the sample box lid and outer can are coated with a blackbody absorber (blue). Coaxial readout lines are filtered using 50 Ω matched metal powder filters (green). The entire sample stage lies within a magnetic shield (grey), attached to the cryostat's 4 K stage. The radiator is used for Fig. 4.

exponentially, consistent with a thermal quasiparticle density (dashed line, Eq. (1)). At low temperatures a plateau value of 10^5 is observed, consistent with an excess quasiparticle density of 230 μm^{-3} (bottom solid line). When using our infrared shielded sample stage ("multistage shielding"), which we discuss below, quality factors of the *same* resonators improve to $2 \cdot 10^6$ (closed symbols). This shows that excess quasiparticles, generated by stray infrared light, are the dominant loss mechanism in Al resonators when using typical shielding.

We have built a light-tight sample stage which uses a "box-in-a-box" design, following Baselmans *et al.*[15] A maximally light-tight design is shown in Fig. 2. The sample box is placed in a larger box in which the *photon* temperature is equal or very close to the *electron* temperature. This is achieved by blocking routes for stray light to enter as well as using black coating. The black coating is a key ingredient and consists of a mixture of silica powder, fine carbon powder, and 1 mm SiC grains in stycast epoxy.[16] The coating has a rough surface, having an absorptivity of 90% over a wide angle in the 0.3-2.5 THz range.[16] The coax filters have a 50 Ω impedance, and we used bronze and carbon powder as an absorber along with a NbTi central conductor, following Ref. 17. At 4.2 K, the transmission up to 20 GHz is given by $S = Af$, with $A = -0.18$ dB/GHz. We estimate that 4.2 K radiation is reduced to a power below 100 fW, excluding additional absorption by the carbon. We used an adiabatic demagnetization refrigerator (ADR), with a base temperature of 50 mK. The sample stage was attached to the 50 mK cold finger of the ADR. For readout, we used two 0.86 mm diameter CuNi coaxial cables, connected between the 4 K stage and the coax filters.

We tested the influence of key parts of the setup. We measured the effect of the: (1) outer can, (2) black coating on the outer can and/or sample box lid, (3) coax filters, and (4) seams in the outer box. In order to quantify the influence of stray light we used halfwave CPW Al resonators with a film thickness of 52 nm, which are coupled capacitively to a feedline (inset Fig. 1). The central line width is 3 μm and the gap width is 2 μm. The unloaded quality factor Q_i, which is reciprocal to the quasiparticle density (Eq. (1)), is extracted from the feedline transmission. We measured quality factors at high power (approximately 10^6 photons in the resonator) to reduce the influence of two-level systems.[3,4] We used halfwave resonators, where the central line is galvanically isolated, to rule out quasiparticle outdiffusion and hot electrons.

The influence of stray light was quantified by continuously measuring the quality factors of the resonators while warming up the cryostat at the 4 K stage, bathing the sample stage in a hot thermal photon bath. While doing so, the sample stage temperature was always kept below 150 mK where the quality factor is unaffected. The sample space was shielded by a cryogenic magnetic shield, attached to the 4 K stage. The transmission was measured using a vector network analyzer, a low noise cryogenic, and room temperature amplifier.

The effectiveness of the shielding methods is shown in Fig. 3. When not using any shielding (outer can, coax filters, or a coated sample box lid), a loss of 10^{-5} is found, which increases strongly with cryostat temperature (red squares). When adding a coated sample box lid and coax filters, a loss on the order of 10^{-6} is found at the lowest cryostat temperatures (red dots). However, here the loss also increases with elevating cryostat temperature. Light-tightness is somewhat improved when adding an uncoated can or covering the sample box with Al tape (purple triangles). The largest improvement is observed when using a coated can, although a small cryostat temperature dependence is still visible. Only when using a coated can and a coated sample box lid is the lowest loss achieved and the dependence on the cryostat temperature fully removed (blue stars). When a 0.5 mm gap is introduced a small temperature dependence returns.

The data in Fig. 3 follow only approximately a pure blackbody radiation dependence for the unshielded case. For a pure blackbody: $P \propto T^4$, and hence $1/Q \propto T^2$ (solid line).

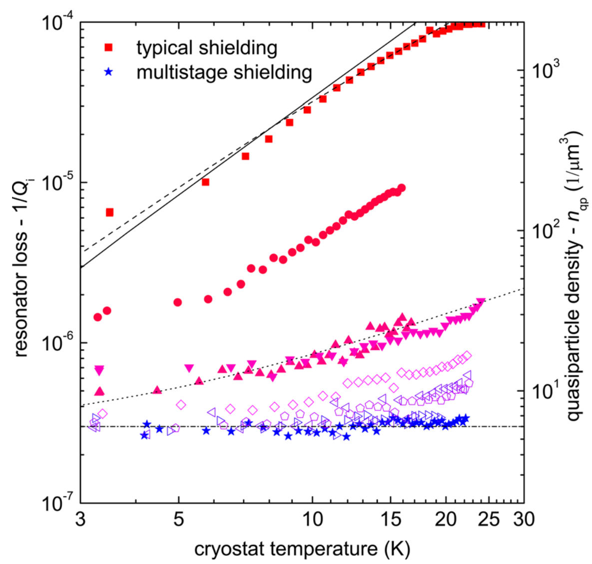

FIG. 3. (Color online) The loss of an Al resonator versus cryostat temperature, showing the influence of different shielding techniques when going from no infrared shielding (■) to fully shielded (★). Right axis shows the corresponding quasiparticle density. The sample stage temperature is kept below 150 mK. Variations in the presence of a coated sample box lid and coax filters (closed symbols, red colors): no can present (●), sample box covered with Al tape (▲) and uncoated can present (▼). Variations in the presence of a coated outer can (open symbols, purple and blue colors): coated can floating on 0.5 mm spacers (◇), uncoated sample box lid and no coax filters (⬠), uncoated lid and filters (◁), coated lid and no filters (▷). Influence of a hot blackbody (solid), hot blackbody filtered with a cut-off frequency at 1 THz (dashed), filtered with a cut-off frequency at 100 GHz (dotted), and no dependence (dash dotted).

With increasing shielding the slope of the data decreases, consistent with the sample stage acting as a low pass filter. We model this as a first order filter with transfer function: $1/(1+[f/f_c]^2)$, with cut-off frequency f_c. We find for the unshielded case: $f_c \sim 1$ THz (dashed line). With Al tape or an uncoated can: $f_c \sim 100$ GHz (dotted line). With each additional shielding step the loss drops—indicating enhanced insensitivity to stray light—and the slope decreases—indicating a decrease of the cut-off frequency. This suggests that low frequency photons are the main source of loss in partly shielded environments.

The data in Fig. 3 demonstrate that a box-in-a-box design with black coating is needed to ensure the removal of the influence of stray light and that anything less is insufficient. An uncoated outer can increases the quality factor to above 10^6 at 3 K but does *not* completely remove the influence. Only when using a coated can and sample box lid is there no dependence on the cryostat temperature. This temperature is varied from 3 to 23 K, increasing the stray light power by 10^3. Moreover, a tight fitting of the outer can is unnecessary as a 0.5 mm gap has only a small effect on the quality factors at 3 K. Using a coated can is more effective than having it tightly fitting. The coax filters are insignificant for our mount, possibly due to the use of dissipative CuNi cables.

The resonator quality factors improve to $2 \cdot 10^6$, and this value is believed to be unrelated to stray light because of its insensitivity to the cryostat temperature. We estimate a lower limit of 10^8 due to stray light, consistent with a light-induced quasiparticle density of 0.2 μm^{-3}, when assuming a level equal to the noise at 23 K in Fig. 3 and extrapolating to 3 K and assuming $f_c = 100$ GHz. The remaining loss mechanism may be radiation loss or excess quasiparticles from some other mechanism, as suggested by recent number fluctuation measurements.[9] In this case the quasiparticle density has been reduced to 10 μm^{-3} (top solid line in Fig. 1) or below.

We also quantified the influence of stray light on the energy relaxation time T_1 of a phase qubit. With the filters and black outer can in place, we find a T_1 of 450 ns, consistent with typical values for phase qubits. In addition, we find no dependence on the cryostat temperature, as shown in Fig. 4. In contrast, when only the outer can is removed T_1 drops to 120 ns. This value is compatible with a quasiparticle density of 170 μm^{-3},[18] close to the value of 230 μm^{-3} found for the resonators. Without an infrared shield, T_1 decreases very rapidly with increasing cryostat temperature. We instead used a blackbody radiator, which was placed behind the magnetic shield (see Fig. 2) and heated up to a stable temperature. We emphasize that the radiator has a weaker influence than the cryostat. The energy relaxation rate clearly increases with the radiator temperature. The decrease in T_1 as well as the temperature dependence in Fig. 4 show that stray light considerably diminishes qubit coherence. It is therefore vitally important for qubit coherence to use a light-tight sample stage, as shown in Fig. 2.

In conclusion, we have found that quasiparticle generation due to stray infrared light from the environment negatively impacts quality factors and energy relaxation times. Moreover, present device performance is often limited by stray light, inducing an excess quasiparticle density between 170 and 230 μm^{-3}. We show that this influence can be removed using a "box-in-a-box" design with black absorbers, and we estimate a lower limit of 10^8 for resonator quality factors due to stray light.

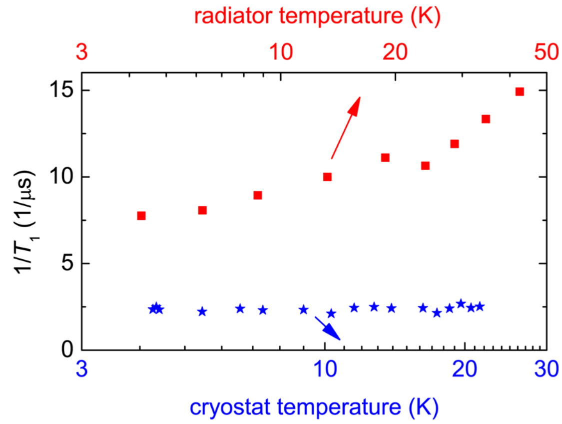

FIG. 4. (Color online) Phase qubit energy relaxation rate measured in the light-tight setup versus cryostat temperature (★) and measured without the presence of a coated outer can versus temperature of a radiator (■) (see Fig. 2). The sample stage temperature is kept below 150 mK.

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