A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

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Abstract. We propose a novel multilayer structure based on Bragg layers that can protect a superconducting microwave resonator from photons and blackbody radiation and have little effect on its quality factor. We also discuss a hybrid quantum system exploiting a superconducting microwave circuit and a two-color evanescent field atom trap, where surface-scattered photons and absorption-induced broadband blackbody radiation might deteriorate the system.
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

**Figure 1.** The conceptual figure (a) (Side-view, not-to-scale) A nanophotonic atom trap has surface-scattered photons. Input optical powers of trapping beams create absorption-induced heat due to a small cross-section area of the waveguide, and the local temperature of the waveguide creates BBR. The PL can be fabricated above the SC MW circuits, and the MW magnetic field through the PL can be coupled to trapped atoms. (b) (Top-view, not-to-scale) The trapped atoms with a nanophotonic waveguide can be transported near the inductor of the thin-film lumped-element SC LC resonator. The remained area of the resonator could be protected by a floated, shielding box anchored at a cooling stage having more cooling power than the sample stage [9].

1. **Introduction**

Hybrid quantum systems [1–4] have been proposed and studied for coherent quantum interfaces and quantum information. A particular implementation [2] uses a two-color evanescent field atom trap with a nanofiber/waveguide [5, 6], coupling cold neutral atoms to a superconducting (SC) microwave (MW) circuit [7, 8] through a magnetic dipole interaction. Optically-trapped cold neutral atoms must be situated near the SC MW circuits to achieve single MW photon operation because a reasonably strong magnetic dipole interaction is required. In the evanescent field atom trap, special care must be taken to protect against scattered laser light and blackbody radiation (BBR), which limits the quality factor (Q) of the SC MW circuits by breaking Cooper pairs [9]. We believe that the design of a protection layer (PL) for near-infrared (NIR) optical fields and broadband mid-infrared (MIR) radiation is necessary for this hybrid quantum system and its related applications. In addition, thermal excitations must be lower than a single MW photon, and limited cooling power at the coldest stage of the dilution refrigerator also needs to be considered.

In this paper, we study a novel PL to help address the problems that arise from coupling evanescent field trapped atoms with a SC MW resonator. We design multi-wavelength Bragg reflectors/absorbers (protection layer) of two NIR wavelengths and a broadband MIR BBR spectrum to protect the SC MW resonator. The thin PL is designed to minimize attenuation of the SC MW fields through the layer and reduced Q-factors of the SC MW resonator.
2. Design and Simulation

Our goal is to design a PL for SC MW circuits which protects against optical photons and BBR. For the magnetic dipole coupling between trapped atoms and SC MW magnetic fields, the back-transmission of SC MW fields through the PL needs to be maintained, and MW dielectric dissipation by PL materials, the reduced Q-factor, needs to be considered. For the coherent quantum interface between SC MW circuits and cold neutral atoms, one may use a two-color evanescent field atom trap such as a nanofiber/waveguide [5,6]. The PL should achieve high reflection and low transmission at the wavelengths of both the narrow NIR trapping lights and the absorption-induced broad MIR BBR. The BBR protection is necessary because optical absorption will heat the nanofiber/waveguide and induce BBR. In this paper, we consider three types of PLs, (i) a typical dielectric distributed Bragg reflector (DBR) layer, (ii) a lossy DBR layer including a thin, nanostructured metallic layer such as gold, and (iii) a lossy DBR layer including a thin, nanostructured conductive dielectric layer such as indium tin oxide (ITO) as illustrated in Fig. 2. An exemplary waveguide geometry based on the reference [6] is used.

Firstly, we design the optical DBR layer for high reflection ($>99.9\%$) of two-color trapping beams (750 nm and 1064 nm), considering the Bragg condition $\lambda/(4n_i)$, where $n_i$ is an index of refraction. The bandwidth of stopbands is linearly proportional to the index difference $n_1 - n_2$ between two neighboring materials [10], in practice less than $\sim 2$. Secondly, we design a broadband MIR Bragg reflector [11]. The MIR Bragg reflector with high reflection and wide bandwidths is obtained by high index difference; the high index difference is practically constrained by material selection. The thin layer-thickness is required for a good magnetic dipole coupling between trapped atoms and the magnetic field of a single MW photon because the magnetic field that is proportional to the square root of a photon number decays with distance. Therefore, it is challenging to design a broadband MIR reflector, operating in single MW photon regime and covering a wide range of BBR temperatures because a longer wavelength means a thicker DBR
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

layer that limits the magnetic dipole coupling.

Assume a multilayer structure as illustrated in Fig. 2 (a). Simply based on Airy’s formula, the reflection coefficient for the multilayer structure as illustrated in Fig. 2 can be calculated [10]. When each layer thickness is designed to be $\lambda/(4n_i)$, reflectivity from a conventional design of reflector can be expressed as

$$R = \left[ \frac{1 - \frac{n_{\text{sub}}}{n_{\text{air}}} \left( \frac{n_2}{n_1} \right)^{2N}}{1 + \frac{n_{\text{sub}}}{n_{\text{air}}} \left( \frac{n_2}{n_1} \right)^{2N}} \right]^2,$$

(1)

where $n_1$ and $n_2$ ($n_1 > n_2$) are refractive indices of the repeating layers and $n_{\text{air}}, n_{\text{sub}}, N$ are refractive indices of substrate and air, and the number of pairs, respectively. Total thickness of PL is determined by the number of pairs $N$. One may decide number of pairs $N$ depending on design limitations such as material indices and reflectance allowed for desired performance. From Eq. (1), we have

$$N = \frac{1}{2} \log \left( \frac{1 - \sqrt{R}}{1 + \sqrt{R}} \right) + \log \left( \frac{n_{\text{air}}}{n_{\text{sub}}} \right) \log \left( \frac{n_2}{n_1} \right).$$

(2)

From Eqs. (1) and (2), we note that for large $N$, the reflectivity $R$ approaches unity as a function of $N$ and the total thickness is $N \cdot (d_1 + d_2)$ excluding substrate. Special care must be taken to note that the substrate index affects performance.

The high index material for the first layer can be either silicon nitride (SiNx, $n_{\text{SiNx}} = 1.9 – 2.4$) or titanium oxide (TiO$_2$, $n_{\text{TiO}_2} = 2.5 – 2.9$) [12, 13]. The second layer can be either magnesium fluoride (MgF$_2$, $n_{\text{MgF}_2} = 1.38$) or a low index polymer material such as Cytop, $n_{\text{cytop}} = 1.38$ [14]. By making the operating resonant wavelength even number multiples, that is, $\lambda = m \times \lambda_{\text{res}}$ ($\lambda_{\text{res}}$: resonant wavelength), we can achieve smaller free spectral range (FSR) and have $\sim 99\%$ reflection at both wavelengths of interest. We use thicker layers so that $d = m\lambda/(4n_i)$, where $m$ is an even number integer. The even number can be slightly tweaked to cover both wavelengths. In this example, it turns out that when $m = 7.1$, the reflectances reach $\sim 1$ at both wavelengths of two-color trapping beams. Fig. 3 (a) shows calculated reflectance as a function of frequency, using SiNx and cytop, and $N_{\text{pairs}} = 5$. Unlike the highly reflective properties at two NIR wavelengths, the reflectance at MIR range $5 – 100$ $\mu$m does not cover broadband emission well because of the nature of a broad BBR spectrum. As shown in Fig. 3 (a), the BBR spectra corresponding to assumed blackbody temperatures 300 K, 400 K and 500 K range from 0 to 200 THz. To see how much energy can be reflected or transmitted, we define reflected and transmitted BBR efficiencies using the overlap integral in the form

$$R_{\text{BBR}} = \frac{\int_{0}^{\infty} S_{\text{BBR}}(\nu, T) \cdot |r(\nu)|^2 \, d\nu}{\int_{0}^{\infty} S_{\text{BBR}}(\nu, T) \, d\nu}, \quad T_{\text{BBR}} = \frac{\int_{0}^{\infty} S_{\text{BBR}}(\nu, T) \cdot |t(\nu)|^2 \, d\nu}{\int_{0}^{\infty} S_{\text{BBR}}(\nu, T) \, d\nu},$$

(3)

where $S_{\text{BBR}}$ is a BBR spectrum as a function of frequency and temperature, and $r(\nu)$ and $t(\nu)$ are reflection and transmission coefficients, respectively.

The small mode area of optical waveguides may induce an intensified optical field, and it heats the waveguide core (SiNx), SiO$_2$ layer, and its Si substrate. In a case of
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

an optical nanofiber, the BBR from a sub-wavelength structure can be calculated with computational electrodynamics \[15\]. Simply based on Stefan-Boltzmann law, the power radiated from BBR is \( P = \varepsilon(\omega, T)\sigma AT^4 \), where \( \varepsilon(\omega, T) \) is an emissivity as a function of a radiation frequency and a temperature. \( A, \sigma, \) and \( T \) are the surface area of an object, Stefan-Boltzmann constant, and a temperature of an object, respectively. The maximally allowable BBR temperature on SC MW circuits without a PL is estimated as \( T_0 = 27.2 \text{ K} \) with a geometric factor (see Appendix D). The PL could reduce BBR transmitted to the SC MW circuits and increase this \( T_0 \), but Stefan-Boltzmann law following \( T^4 \) limits the BBR protection on SC MW circuits. The BBR radiated power \( (T > 100 \text{ K}) \) would be quite difficult to protect in single MW photon operation \( (N_{\text{pairs}} = 5) \).

Five pairs \( (N_{\text{pairs}} = 5, \text{ thickness } = 14 \mu\text{m}) \) of dielectric multilayer structure seem highly reflective, almost 100% (transmission \( \simeq 10^{-3} \)) at both NIR wavelengths as shown in Fig. 3 (a), whereas the transmitted BBR efficiency \( T_{\text{BBR}} \) defined in Eq. 3 is estimated to be 27, 30, and 39% at 300, 400, and 500 K, respectively, which may not suffice in this applications because a substantial transmitted BBR may deteriorate behavior of SC MW circuits by thermally excited quasi-particles. Simply adding a thin, nanostructured metallic or conductive dielectric layer in each pair of layers improves the efficiency of protection in a BBR spectrum \[16\] as shown in Fig. 2 (b). Thin metal such as Au can be easily deposited and patterned on any polymer and semiconductor surfaces.

We show numerical simulation in the case of adding repetitive 2 nm nanostructured Au layer below \( n_2 \) as shown in Fig. 3 (b). Note that the reflectivities are still close to 1 at both wavelengths, and the transmitted BBR efficiency \( T_{\text{BBR}} \) calculated from Eq. (3) is less than 3% until 500 K. However, planar metal structure can cause magnetic-field-induced losses resulting from eddy currents, which affect the SC MW circuit operation. Patterned nanostructure smaller than operating wavelength (less than a few microns) can drastically minimize this effect because of localized magnetic vortices. Optical properties of a subwavelength nanostructure can be approximated by Maxwell-Garnett’s effective medium theory \[17\] as given in

\[
n_{\text{eff}} = n_m \sqrt{\frac{2(1-\delta)n_m^2 + (1+2\delta)n^2}{(2+\delta)n_m^2 + (1-\delta)n^2}}, \tag{4}
\]

where \( n_m, n, \) and \( \delta \) are the refractive indices of the metal, the dielectric, and the volume portion of dielectric material, respectively.

Figure 4 shows angle dependency of our PL from DC to 500 THz. In the practical design, the light scattering and the BBR can be incident obliquely at a certain angle of incidence. As seen in the Fig. 4 MIR region does not change much, but optical region shows some variation depending on the incident angle. The PL is located in the coupling region between cold atoms and a SC MW circuit. Most spurious waves from the optical waveguide are emitted vertically to the PL on top of the SC MW circuit and reflected/absorbed, but the oblique wave will pass through the PL. Fig. 4 shows transmission behaviors at NIR and MIR region. Note that transmissions are still
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

Figure 3. (a) Reflectivity (R) in conventional Distributed Bragg reflectors using five pairs of TiO$_2$ and cytop polymer and $d = 7.1\lambda/(4n_i)$ instead of $d = \lambda/(4n_i)$. Red line shows reflectance at NIR and MIR ranges. (b) Absorption (A) and transmission (T) in lossy reflectors with thin metal layers. (c) A and T in lossy reflectors with thin conductive dielectrics (TiO$_2$).
**Figure 4.** The transmission of oblique incident fields for lossy reflectors with thin conductive dielectrics (TiO\(_2\)). The incident angles of 0\(^\circ\), 15\(^\circ\), and 30\(^\circ\) are shown; Fig. 3 (c) is related to the case of an 0\(^\circ\) incident angle.

**Figure 5.** The absorbed optical power per unit volume (W/m\(^3\)) through the PL. In the case of lossy reflectors with thin conductive dielectrics, the surface scattered light is absorbed at the TCO layers. The absorbed optical power of the first TCO layer (2 nm thin) is 240 nW from a 1mW scattered light that would radiate uniformly.

acceptable within ±15\(^\circ\) ranges.

We estimate the surface scattering loss per the surface roughness variance from the waveguide structure (see Appendix C). The scattering loss of a strongly guided mode at 1064 nm light can be around 0.05 (dB/cm)/nm\(^2\) [18–20]. Then, the top-surface scattering power per unit length is about 340 \(\mu\)W/cm from 30 mW input optical power with a surface roughness variation of 1 nm\(^2\). The side-surface scattering is expected to be higher due to etching process, but we could neglect this because of the locations of a shielding box, a nanophotonic atom trap, and a SC inductor line.
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

Figure 6. The back-transmission of SC MW fields in the cases of a dielectric DBR layer (black), a lossy DBR layer with conductive dielectric layers (blue), and a lossy DBR layer with thin metallic layers (red).

Figure 7. The Q-factor of a thin-film lumped-element SC LC resonator with a PL depending on dielectric loss tangents of $n_1$ and $n_2$ dielectric layers. An effective conductivity for void structures is also defined for a conductive oxide layer $n_3$.

as shown in Fig. 1(a). The SC MW circuit is exposed to a small light scattering angle of about $1^\circ$; $\theta_{\text{photon}} = \tan^{-1}(0.5w_{WG}/d_{WG-SC})$, where the waveguide width is $w_{WG} = 800$ nm and the distance from the waveguide to the SC MW circuit is $d_{WG-SC} = 20 \mu$m. The geometric factor of top-surface scattering is estimated as $2 \cdot \tan^{-1}(0.5w_{SC}/d_{WG-SC})/180^\circ = 2 \cdot 7.2^\circ/180^\circ \approx 0.08$, where the SC MW circuit-line width is $w_{SC} = 5 \mu$m. A 340 $\mu$W/cm scattered light on a 0.04 cm-long SC inductor line can be reduced to 1.1 nW on the coupling area by the geometric factor (0.08) and the PL (10$^{-3}$ transmission with $N_{\text{pairs}} = 5$ and layer thickness = 14 $\mu$m). If the BBR is not a major concern for the hybrid quantum system, we could make 10 pairs of multilayers with a 3 $\mu$m-thin PL and 10$^{-5}$ – 10$^{-6}$ optical transmission suppression. Then, we could have 10 pW - 1 pW transmitted optical power which can be close to or lower than 2.4 pW, the upper bound of the quasi-particle generation which does not affect the Q-factor of a SC MW resonator [21]. For an optical nanofiber (ONF) with
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

2.6 × 10^{-4} \text{dB/cm} \text{ propagation loss} \ [22], 1.8 \mu \text{W/cm} \text{ scattered light out of 30 mW optical power on a 0.04 cm-long SC inductor line could be reduced to 2.8 pW on the coupling area with the PL and the geometric factor \((2 \cdot 7.2^\circ/360^\circ = 0.04)\). Then, the Q-factor of a SC MW circuit can be maintained \qref{21}.

The absorption-induced heat flux \(H_{\text{abs}}\) in a waveguide is estimated from the extinction coefficient \(\kappa\) of SiNx. For an example, an input heat flux is \(H_{\text{abs}} = P_0/A_{\text{wg}} \cdot (1 - \exp(-2 \cdot \frac{2\pi}{\lambda} \cdot \kappa \cdot l_{\text{wg}})) = 1.57 \times 10^5 - 10^6 \text{W/m}^2\) with \(\kappa = 10^{-11} - 10^{-10}\), where the input optical power \(P_0 = 30 \text{ mW}\), the effective mode area \(A_{\text{wg}} = 800 \text{ nm} \times 300 \text{ nm}\), and a waveguide length \(l_{\text{wg}} = 1 \text{ cm}\) (see Appendix C). A 300 nm-thick SiNx waveguide is deposited on SiO}_2 layer and Si substrate, and this sample is supposed to be anchored at the 3.5 K cooling stage. The highest temperature of the SiNx wave guide is about \(4.2 - 10.3 \text{K}\) in COMSOL, Inc.; the heat transfer simulation considers heat conduction through the materials, and buffer-gas cooling at a pressure less than \(10^{-10}\) mbar in a dilution refrigerator can be neglected due to cryo-pumping. For a 1 cm-long nanofiber with 500 nm diameter, 30 mW input optical power corresponds to \(\sim 750 \text{K}\) in a room temperature vacuum chamber \qref{23} and corresponds to \(\sim 450 \text{K}\) when a fiber having a 1 cm-long nanofiber section and non-tapered fiber ends is attached to a U-shaped metallic holder; the metallic holder is anchored at the 3.5 K cooling stage. The heat conduction of a nanofiber is several hundred times worse than that of a SiNx waveguide because of its geometry; a longer non-tapered fiber induces more heat due to its lower heat conduction efficiency.

The absorbed power at the thin conductive layer \qref{24} has been studied in Fig. 5. The lossy reflector can suppress the transmission of the optical fields and have broad stop bands for preventing the BBR, but the absorbed power in the PL could heat up the sample stage. The total heat has to be lower than the cooling power of 100 mK cooling stage \((200 - 400 \mu \text{W})\). From the waveguide sample, a 1 mW line source’s intensity is assumed to be radiated uniformly, and we estimate the intensity on the PL. We can calculate the electric field square in the PL and estimate the absorbed power per unit volume with \(Q_A = (2\pi\epsilon_0 n_A k_A/\lambda)|E_A|^2\), where \(n_A\) and \(k_A\) are given by \(n_A + i \cdot k_A = \sqrt{\epsilon_A(\omega)}\), and \(E_A\) is the electric field component of the optical field in the PL. In the first TCO layer, the absorbed optical power is \(P_{\text{abs}} = Q_A \cdot V_A \simeq 0.5 \mu \text{W}\), where \(Q_A = 2 \times 10^{10} \text{W/m}^3\) and the volume \(V_A = 30 \mu \text{m} \times 400 \mu \text{m} \times 2 \text{ nm}\) with a 2 nm thin conductive layer. The absorbed powers of other layers decrease, and the total absorbed power has to be lower than the cooling power of the sample stage.

We need to consider the attenuation and reflectance of the SC MW fields \((6.835 \text{ GHz})\) because the coupling between a thin-film lumped-element SC LC resonator and optically trapped cold neutral atoms requires a magnetic field with low microwave loss. We checked the attenuation of SC MW fields, considering a microwave frequency up to 50 GHz, for a lossy DBR layer with TiO}_2 as shown in Fig. 6. The attenuation of SC MW fields is also an important issue to consider in the PL design as in Fig. 6. We assume that the near-field AC magnetic field can be treated using the plane-wave approximation. The dielectric DBR layer has a low MW attenuation less than 10%,
but the narrow stop-bands of the PL cannot cover the full range of the BBR. Adding absorptive nanostructured metallic thin-films can suppress the transmission of a MIR BBR to the SC MW circuits, but the attenuation of SC MW fields is drastically increased more than 90% and the partially absorbed MIR and NIR energy might heat up the device. An absorptive layer with conductive dielectrics such as TiO$_2$ can reduce SC MW fields less than 60% while the transmissions for both NIR and MIR radiations can slightly increase. The electric field and the magnetic field of the SC MW resonator are localized at the capacitance part and at the inductor part, respectively in the near-field regime. We checked the transmission of SC MW magnetic field distribution through the PL in HFSS simulation. The simulation results were similar to that with the plane-wave approximation.

The dielectric layers or dielectric thin-films on the thin-film lumped-element SC LC resonator affect the Q-factor because the dielectric materials induce loss by TLS dissipation having both temperature and MW power dependencies. The TLS dissipation could be mimicked with the classical dielectric loss tangent tan$\delta$ in HFSS simulation. In the case of the lossy DBR layer with conductive oxide, we set the first and second dielectric layers with conductive layers as follows: $0.98\,\mu m$-thin $n_1$ Bragg layer ($\epsilon_r = 6$, $\mu_r = 1$, tan$\delta = 10^{-4}$), $1.83\,\mu m$-thin $n_2$ Bragg layer ($\epsilon_r = 2$, $\mu_r = 1$, tan$\delta = 10^{-4}$), and $2\,nm$-thin $n_3$ conductive oxide layer ($\epsilon_r = 100$, $\mu_r = 1$, $\sigma_{eff} = 2.8\,S/m$) are defined at the MW regime. The void structures reducing vortex-induced loss have a lower effective conductive loss depending on the ratio of voids as given in Eq. (4). The conductivity $\sigma_{eff}$ of $n_3$ layer without void structures is estimated as 27.8 S/m with tan$\delta = 0.5$ [26]. For the loss tangents of dielectric layers tan$\delta = 10^{-5}$ to $10^{-2}$, the Q-factors of a thin-film lumped element SC LC resonator with a PL is simulated in Fig. 7; the Q-factor with no PL is $1.2 \times 10^7$ with the Sapphire substrate (tan$\delta = 1 \times 10^{-7}$). The PL with tan$\delta < 10^{-3}$, giving $Q > 5 \times 10^5$, would not affect the SC resonator in the range of Q-factor.

3. Discussion

There exists several important issues to be considered for designing the PL. The magnetic dipole coupling between trapped atoms and MW magnetic fields decides the layer thickness of the PL because a weak magnetic field of a single MW photon requires a closer distance less than $20\,\mu m$ between trapped atoms and a SC MW resonator for a reasonably strong coupling strength that can resolve atomic signals. A strong magnetic field of classical MW fields can couple to cold neutral atoms with an enough coupling strength at a further distance, which means that a PL can exploit a thicker layer having an increased number of Bragg layers; we can design a nearly perfect PL for a two-color NIR optical field and a broad MIR BBR with wide stop bands.

The thickness of the PL is mostly determined by a BBR wavelength. The Bragg condition $\lambda/(4n_i)$ of the BBR leads to a thicker layer compared to that of two-color trapping beams ($750\,nm$ and $1064\,nm$) because a peak-wavelength of BBR is a few $\mu m$,
and BBR with a lower temperature has a longer peak-wavelength; the peak-wavelengths of the BBR corresponds to 9.66 µm for 300 K and 5.8 µm for 500 K. However, if the BBR protection is not considered in such a case of a free-space optical trap, we can increase the number of optical Bragg layers to minimize the transmission of optical fields for a given thickness of the PL. The transmission of optical fields can be suppressed as $10^{-5} - 10^{-6}$ with $N_{\text{pairs}} = 10$ from the transmission of $10^{-3}$ with $N_{\text{pairs}} = 5$.

A lossy DBR layer with thin, nanostructured conductive layers in each pair of layers has a better suppression of a BBR spectrum; a thin nanostructured layer consists of a sub-micrometer grid-structure. This grid-structure will decrease the bulk conductivity of the conductive layer and minimize the induced-current loss. A thin Au, non-SC material, without the thin grid-structure could not be used as the PL on the SC MW circuits because the induced-current in the layer prevents the magnetic field of SC MW circuits to penetrate through the layer.

For general applications of protecting SC MW circuits, a floated, shielding box anchored at a higher temperature cooling stage than the sample stage could be useful (see Fig. 1). The inner part of this shielding box has absorptive layers, and the outer part of the box has reflective layers. Without considering the magnetic dipole coupling in such a case of a hybrid quantum system, multiple stop bands and an increased number of Bragg pairs are usable for the selected spectrums of broad MIR and NIR radiations. In addition, lossy Bragg layers with conductive layers can be utilized more on the inner and outer parts of the box because we would not worry about the attenuation of SC MW fields. Eventually, we could realize a better blackbody transmission-suppressor, reflector, and absorber.

4. Conclusion

We propose the novel PL of SC MW circuits for the future study of a hybrid quantum system incorporating a two-color evanescent field atom trap because the vulnerability of SC MW circuits from optical photons and BBR brings practical limitations of coupling evanescent field trapped atoms to the SC MW circuits. In the case of the evanescent field atom trap with a nanofiber/waveguide, surface-scattered NIR optical photons and absorption-induced BBR have to be blocked. Firstly, we maximize the reflection and minimize the transmission of optical photons and BBR, and this is an optimal design issue of a multi-wavelength dielectric Bragg reflector that covers two-color NIR optical trapping beams and a broadband MIR BBR. Secondly, the lossy dielectric reflectors with thin, nanostructured metallic or conductive dielectric layers can protect SC MW circuits better in a broad BBR spectrum, but it has more attenuation of the SC MW magnetic field compared to the dielectric Bragg reflector. This lossy dielectric reflectors have more absorbed optical photons at thin conductive layers, and the absorption has to be considered carefully as a potential heat source limiting the cooling power of the coldest stage. In the development of a hybrid quantum system with SC MW circuits and cold atoms, the suppression of the quasi-particles created by light scattering and
BBR requires the PL, but the TLS interaction loss in the dielectric material also reduces the Q-factor of a SC MW resonator. In addition, the back-transmission of the SC MW magnetic field through the PL needs to be considered for a reasonably strong magnetic dipole coupling. Therefore, the PL’s overlapping volume between the electromagnetic fields of the SC MW circuits and the layer thickness needs to be minimized. In the case that we consider only optical photons, a large numbers of optical DBR layers with an extremely high suppression rate are possible and promise a high reflectivity which could be used in a harsh condition of a free-space optical dipole trap. This is expected to be helpful for coupling Rydberg atoms or trapped ions to the SC MW circuits. The general studies of reflective or absorptive Bragg layers [16] preventing NIR and BBR radiations with multiple floated, shielding boxes anchored at a higher temperature cooling stage than the sample stage can be applied to improve the coherence times of SC qubits further in the dilution refrigerator [9].

Acknowledgements

This research is funded by the ARO Atomtronics MURI. The authors would like to thank S. L. Rolston, J. B. Hertzberg, and all team members of the PFC@JQI ‘Atoms-on-SQUIDs’ project for useful discussions.

Appendix A. Hybrid quantum system with superconducting microwave circuits and cold neutral atoms

The magnetic dipole coupling of cold neutral atoms to SC MW circuits was proposed for a hybrid quantum system [1]. The hyperfine transition of $^{87}$Rb atoms respond to the magnetic field of the SC MW resonator. This coupling happens through magnetic dipole interactions of $-\hat{\mu}_B \cdot \vec{B}$, where $\hat{\mu}_B$ is the atomic magnetic dipole moment.

A thin-film lumped-element superconducting LC resonator

We use a thin-film lumped-element SC LC resonator with 300 nm film thickness and 5 $\mu$m circuit-line width. The lumped-element circuit has the advantage of a single resonant frequency and a compact size in the near-field regime of several hundred by several hundred square micrometers. Therefore, the RF electric field is localized at the capacitance part, and the RF magnetic field is localized at the inductor part. The magnetic dipole interaction happens through a SC inductor line. For a high MW photon number such as $5 \times 10^4$, an Al thin-film lumped-element SC LC resonator has a quality factor $Q = \omega/\delta\omega \simeq 2 \times 10^6$ at $\omega_{MW} = 2\pi \cdot 6.835$ GHz and a cavity linewidth $\delta\omega = 2\pi \cdot 3.4$ kHz (FWHM). For a low MW photon number less than 100, the SC MW circuit has a lower Q-factor such as $Q \simeq 1.5 \times 10^5$ and $\delta\omega = 2\pi \cdot 45$ kHz due to non-saturated TLS dissipation. A reasonably strong coupling strength between SC MW circuits and atoms shifts the cavity resonance, and we can resolve an atomic signal through on-resonant/dispersive MW cavity-photon measurement. Potentially, an
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

atomic qubit coupled to the SC MW resonator can interface with a SC qubit coupled to the SC MW resonator.

Nanophotonic atom trap

A nanophotonic atom trap creates optical potentials that confine atoms along the transverse directions with the differential decay lengths of two-color traveling evanescent wave fields and confine atoms along the propagation direction with a standing wave of red-detuned fields. For a single atomic transition \((\omega_0)\), the induced light shift (AC Stark shift) creates an optical potential. This potential \([27]\) for a large detuning \((\Delta = \omega - \omega_0)\) is \(U_{opt}(r) = \frac{3\pi c^2}{2\omega_0^3} \frac{1}{\Gamma} I(r)\), where \(I(r)\) is the laser intensity, and \(\Gamma\) is the spontaneous decay rate of the excited state. A blue-detuned trapping beam creates a repulsive potential \((\Delta_{blue} > 0)\), and a red-detuned trapping beam produces an attractive potential \((\Delta_{red} < 0)\). For trapping atoms near the surface (\(\sim 200\) nm) of a dielectric, the blue-detuned beam needs to compensate the attractive van der Waals potential. Approximating the surface to be an infinite dielectric, the van der Waals potential is \(U_{vdW}(y) = -C_{vdW} \cdot y^{-3}\), where \(y\) is the distance from the waveguide surface, and \(C_{vdW}\) is determined from atomic dipole transition. The total potential along the vertical direction of the waveguide is \(U_{tot} = U_{blue} + U_{red} + U_{vdW}\). A two-color evanescent field atom trap with the surface light scattering and the absorption-induced BBR creates optically-excited and thermally-excited quasi-particles in the superconductor.

Appendix B. Single microwave photon operation

Magnetic dipole coupling and its coupling strength per atom for single microwave photon operation

The hyperfine transition of \(^{87}\text{Rb}\) between \(|F = 1, m_f\rangle\) and \(|F = 2, m'_f\rangle\) has a microwave frequency of 6.835 GHz, and atoms respond to the magnetic field of a inductor line of the SC MW resonator. This magnetic dipole coupling can be used for a hybrid quantum system \([1]\). In HFSS simulation, we know electric fields and magnetic fields at each location. The stored energy of SC MW fields are assumed to be equally distributed at the local electric field near the capacitor and at the local magnetic field near the inductor. The stored energy of SC MW magnetic field can be calculated by integrating the local magnetic energy over the mode volume. Then, we can estimate the magnetic field of a single MW photon based on the HFSS simulation result. The estimated magnetic field scaled by \(1/\sqrt{\langle n_{ph}\rangle}\) is \(\langle \vec{B} \rangle \simeq 2.1\) nT at 10 \(\mu\)m above the inductor, where \(\langle n_{ph}\rangle\) is an intra-cavity MW photon number in the simulation. From this estimation, a coupling strength per atom for a single MW photon is \(g = \vec{\mu}_B \cdot \langle \vec{B} \rangle / \hbar = 2\pi \cdot 30\) Hz. For \(10^3\) trapped atoms in a two-color evanescent field atom trap, the effective coupling is \(g_{eff} = \sqrt{N}g \simeq 2\pi \cdot 1\) kHz. A SC MW resonator could resolve this \(g_{eff}\), which would operate with \(Q = 5 \times 10^6\) and \(\delta \omega = 2\pi \cdot 1.35\) kHz in low MW photon regime. The waveguide atom trap array coupled to multiple inductors of a SC MW resonator is
expected to increase the number of trapped atoms as $10^4$, and the optimal design of a SC MW resonator with a small cavity mode volume can improve the coupling strength $g$ up to $2\pi \cdot 100 \text{ Hz}$. Then, the effective coupling would be $g_{eff} = 2\pi \cdot 10 \text{ kHz}$. A SC MW resonator could resolve this $g_{eff}$, which would operate with $Q = 6.2 \times 10^5$ and $\delta \omega = 2\pi \cdot 11 \text{ kHz}$ in low MW photon regime.

**Thermal occupation for single microwave photon operation**

Single MW photon operation in SC MW circuits requires a lower thermal occupation (25 mK) than a single MW photon ($328 \text{ mK} = \hbar \omega_{MW}/k_B$) to resolve the single MW photon signal, where $\omega_{MW} = 2\pi \cdot 6.835 \text{ GHz}$ close to the atomic clock frequency of $^{87}\text{Rb}$ atoms. For superconductivity, the operation temperature needs to be lower than the critical temperature of SC materials ($T_{c,\text{Al}} = 1.2 \text{ K}$, $T_{c,\text{Nb}} = 9.3 \text{ K}$). The cooling power of a 3.5 K cooling stage is close to 1 W, but the cooling power of a 25 mK cooling stage is as low as $200 \mu \text{W}$ before reaching 100 mK (Oxford Instruments Triton 200, a dilution refrigerator; the cooling power of 100 mK cooling stage is $200 - 400 \mu \text{W}$). Therefore, the total optical power level from the scattering light of optical trapping beams and the BBR from the waveguide should be lower than this bound for applications.

**Distance between superconducting microwave circuits and trapped atoms for single microwave photon operation**

Single MW photon operation in the SC MW circuits requires a small distance less than 20 $\mu$m above the SC MW circuit for a reasonably strong coupling strength to resolve the atomic signal through the dispersive MW photon measurement [28]. We can estimate the strength of MW magnetic fields at a couple tens of micrometer distance in single MW photon operation, and we design the PL to lie within this distance. Compared to an atom chip that magnetically traps atoms in a few tens of micrometer distance [29] and of which time-varying magnetic field could reduce the Q-factor [30, 31], a two-color evanescent field atom trap with a nanophotonic waveguide [6] can confine atoms in a sub-micrometer distance.

**Appendix C. The estimation of surface-scattered optical photons and absorption-induced blackbody radiation**

**Surface-scattered near-infrared photons**

It is well known that optical losses in waveguides consist of material (both intrinsic and extrinsic) absorption, Rayleigh scattering, and waveguide imperfections [32]. The intrinsic absorption of a nanophotonic atom trap is a heat source because the small mode area of the nanophotonic waveguide makes localized and intense BBR source in the near field. Compared to a nanofiber atom trap [23], the local equilibrium temperature of the ridge waveguide can be lower due to its large substrate area and
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

close thermal-contact with 3.5 K cooling stage. In addition to the intrinsic absorption, the waveguide imperfections contribute direct illumination to SC underneath, while extrinsic absorption and Rayleigh scattering can be relatively small due to smooth surface morphology by the state-of-the-art plasma-enhanced chemical-vapour deposition (PECVD) system or low-pressure chemical vapour deposition (LPCVD) system. Intrinsic absorption is expected to be slightly higher than silica fiber (< 0.5 dB/km) used in modern optical communication system because of the lower bandgap of SiNx. Assuming that the strength of the Lorentzian model for SiNx is comparable with silica, the loss is estimated to be less than 5 dB/km at the wavelength of 750 nm and 1064 nm. In fact, SiNx waveguide with propagation losses less than 0.1 dB/cm at the wavelength of 632 nm had been reported in 1977 and Gondarenko et al demonstrated 0.055 dB/cm at the telecommunication wavelength. A major source of the propagation loss is waveguide imperfections such as surface roughness and an refraction index difference of core and cladding layers. An evanescent field usually operates as strongly-guided modes, where their refraction index difference and propagation loss are higher than those of weakly-guided modes.

We show the surface scattering loss from the waveguide in order to estimate the absorbed optical power per unit volume at the PL on the SC MW circuits (see Fig. 5). Based on a reference, the scattering losses normalized to the roughness variance of SiNx / SiO₂ waveguides (TE-like mode) is 0.01 (dB/cm)/nm² for 800 nm width (core) and 300 nm height (core), where n_{core} = 2.00 and n_{clad} = 1.45 for 1550 nm. After considering the wavelength-dependent scattering losses (\( \alpha_{sc} \propto \frac{1}{\lambda^k} \) (dB/cm) with k = 4.204 for the TE-like mode), the scattering losses for 1064 nm light is 0.05 (dB/cm)/nm². Therefore, the roughness variance of the waveguide determines the scattering losses. If the top-surface of the waveguide has 1 nm² roughness variance, the scattering losses from the top-surface is 0.05 (dB/cm).

Dominant scattering results from the side-wall roughness because of the imperfection of photolithographic waveguide patterns on photoresist before the etching process. In Fig. 1 direct illumination from the top surface of deposited SiNx affects SC MW circuits underneath the waveguide structure. From planar-waveguide loss theory (2D analysis), illuminated power can be estimated based on the surface roughness and the correlation length of the roughness. The scattering losses of the planar waveguide can be modeled more reliably in 3D model, and the loss analysis in 3D is an order of magnitude smaller than the loss analysis in 2D.

Absorption-induced heat and mid-infrared blackbody radiation

For a total optical trapping power of \( P_0 \), the absorbed optical power in the SiNx can be \( P_0 \cdot (1 - \exp(-2 \cdot \frac{\kappa}{\lambda} \cdot l_{wg})) \) with the length of a waveguide \( l_{wg} \) and the extinction coefficient \( \kappa = 10^{-11} \) despite a low intrinsic absorption loss \( \kappa \propto 10^{-12} \) from Ref. 32. The extinction coefficient \( \kappa \) partially resulting in joule heating, excluding Rayleigh scattering portion, is assumed to be less than \( 10^{-10} - 10^{-11} \) at the wavelengths of our interest, based
A novel protection layer of superconducting microwave circuits toward a hybrid quantum system

on the total optical losses. We simulate the thermal gradient with this input heat flux in 2D Comsol simulation with boundary condition (the waveguide sample anchored at 3.5 K cooling stage). This local heat source creates the BBR which should be prevented to protect SC MW circuits from thermally-excited quasi-particles. The BBR spectrum is defined as

$$S_{BBR, \nu}(\nu, T) = \frac{(2h\nu^3/c^2) \cdot 1/(\exp\left(\frac{h\nu}{k_BT}\right) - 1)}{1},$$

where a peak-spectrum frequency of $S_{BBR, \nu}(\nu_{pk}, T)$ is $\nu_{BBR, pk}(T) \approx 2.8214 \cdot k_BT/h$.

Appendix D. Sensitivity and loss mechanism of superconducting microwave circuits

Critical temperature of superconductivity

The critical temperatures of Al and Nb are 1.2 K and 9.3 K, and the SC band-gaps ($E_g \sim 7/2 \cdot k_BT_c$) are 82 GHz ($E_{g, Al}$) and 737.4 GHz ($E_{g, Nb}$), respectively. Therefore, if the energies from BBR and surface-scattered light are higher than these SC band-gap energies, the Cooper pairs are broken into quasi-particles. Generally, NIR optical photons have enough energy to break the Cooper pairs; 400 THz (750 nm) and 282 THz (1064 nm) optical photons have much higher energies than $E_g$. The energy of a BBR spectrum depends on absorption-induced heat and a local temperature gradient. The portion of a BBR spectrum higher than $E_g$ can break Cooper pairs even if a peak-spectrum frequency $\nu_{BBR, pk}(T)$ of the BBR is lower than $E_g/h$.

The minimum acceptable powers of optical photons and blackbody radiation which maintain the Q-factor of a superconducting microwave resonator

In the experiment, the intensity level lower than 100 aW/µm² does not affect much on the operation of an Al SC MW resonator, maintaining its Q-factor higher than 50% of an original Q-factor ($= 5 \times 10^5$) [21]. The SC MW resonator’s inductor part coupled to cold atoms is sensitive to the quasi-particles due to kinetic inductance. The quasi-particles created at the inductor shift the cavity resonant frequency and reduce Q-factor; the overall inductor area of a lumped-element SC MW circuit in the experiment is about $A = 2.4 \times 10^4 \mu m^2$. It corresponds to 2.4 pW level of the maximum acceptable optical power which strikes on the inductor area of the SC MW circuit and creates quasi-particles. We assume that the quasi-particles diffuse and recombine in the steady state, and this optical power is the upper bound of the quasi-particle generation which does not inhibit the superconductivity. Therefore, the atom-photon coupling to a single SC inductor line should be exposed to less than 2.4 pW optical power; in the transient state, the maximum acceptable optical power would be lower because the denser quasi-particles lead to more dissipation.

In addition, we estimate the allowable thermally-excited quasi-particles for the SC MW resonator based on the acceptable power. Based on Stefan-Boltzmann’s law, we can estimate a BBR temperature $T$ by the acceptable power $P$ as follows: $P = \varepsilon A\sigma T^4$, where an emissivity $\varepsilon \approx 1$; the inductor area $A$ of the SC MW circuit; Stefan-Boltzmann
constant $\sigma = 5.67 \times 10^{-8} \text{J/(s} \cdot \text{m}^2 \cdot \text{K}^4)$. Then, the estimated BBR temperature $T$ with 2.4 pW optical power corresponds to $T_0 = 12 \text{K}$; this allowable temperature is estimated by $2.4 \text{pW} / A_1$, where the area of a single inductor line is $A_1 = 1.93 \times 10^3 \mu\text{m}^2$. The dissipation in the transient state depends on the density of quasi-particles, and we might have a lower allowable temperature. Here, we assume that quasi-particles diffuse enough through all enough volume of inductors in the steady state, the coupling area $A_1$ of a single inductor is endurable with the maximum acceptable power of 2.4 pW. Considering the geometric factor of a nanofiber as $0.04 \simeq 2 \cdot \theta_{BBR}/360^\circ = 2 \cdot \tan^{-1}(0.5w_{SC}/d_{ONF-SC})/360^\circ = 2 \cdot 7.2^\circ/360^\circ \simeq 0.04$, the blackbody temperature with the radiated power $P/0.04$ allows a BBR temperature up to $T_0 = 27.2 \text{K}$, where $\theta_{BBR}$ is the radiant angle toward a SC inductor line under the PL, the width of a SC inductor line is $w_{SC} = 5 \mu\text{m}$, and the distance between the SC MW circuit and the ONF is $d_{ONF-SC} = 20 \mu\text{m}$. This allowable temperature could be increased by the number of pairs in the PLs, but the fourth-order temperature dependence in Stefan-Boltzmann’s law limits the upper bound of this BBR temperature.

Two-level system dissipation and dielectric loss tangent

A thin-film lumped-element SC LC resonator has a higher Q in high MW photon regime, but the SC MW resonator has a lower Q in low MW photon regime because of non-saturated TLS dissipation in the SC MW circuit [28]. In single MW photon operation, the reduced Q-factor by TLS dissipation can be estimated classically with realistic dielectric loss tangent values of dielectric thin-films (see Fig. 7) in HFSS simulation. The contribution of TLSs interaction loss is determined by a temperature and a MW power [25]. Compared to the capacitance part, the inductor part is less sensitive to dielectric loss, and a PL layer consists of dielectric layers and thin conductive layers. In addition, the attenuation of SC MW fields through the PL is also considered (see Fig. 6) because the attenuation of MW magnetic fields through the PL affects the magnetic dipole coupling between evanescent field trapped atoms and MW magnetic fields.

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