Superconducting microwave resonant circuits for the detection of photons from microwaves through gamma rays

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Abstract — Thin-film superconducting microwave resonators play an important role in large superconducting photon cameras for applications ranging from cosmology to nuclear non-proliferation. The high quality factor and low loss of these devices make it possible to couple many resonators to a single feedline, enabling frequency-division multiplexing of large arrays of detectors. We review the use of superconducting microwave resonators for both microwave kinetic inductance detectors (MKIDs) and superconducting transition-edge sensors (TES).

Index Terms — Detectors, superconducting microwave devices.

I. INTRODUCTION

The low loss of superconducting materials at microwave frequencies makes it possible to lithographically fabricate thin-film superconducting microwave resonators with extremely high quality factors ($Q > 10^7$ [1]). This remarkable property makes it possible to read out large arrays of superconducting photon detectors, since many high- Q microwave resonators with different resonant frequencies (typically between 1 GHz and 10 GHz) can be frequency-division multiplexed on one coaxial cable. Superconducting microwave resonators are important for the next generation of large superconducting cameras, based on both superconducting transition-edge sensors (TES) [2] and microwave kinetic inductance detectors (MKID) [3]. Arrays of superconducting detectors play an important role in astronomy, cosmology, nuclear physics, materials analysis, and nuclear non-proliferation research.

We review the use of superconducting microwave resonators (Fig. 1) with both MKID and TES detectors. In an MKID, the photon energy creates quasiparticles in the superconducting resonator itself, changing the frequency and Q of the resonator. A measurement of the microwave signal transmitted through a feedline coupled to the resonator can be used to measure either the photon energy or the power in the photon signal. In a TES, the photon energy changes the temperature of a superconducting film biased in the narrow transition region between the normal and superconducting state. The current through the TES creates a magnetic flux in a dissipationless rf SQUID coupled to a microwave resonator. A measurement of the microwave signal transmitted through a feedline coupled to the resonator can be used to infer the photon energy or the power in the photon signal.

Fig. 1. (a) A schematic illustration (not to scale) of one type of lithographic superconducting microwave resonator: a quarter-wavelength coplanar waveguide capacitively coupled to a coplanar waveguide feedline. The superconducting film (e.g. TiN) is shown in grey, and bare Si is shown in white. A microwave signal is injected in port #1, and the transmitted signal S_{21} is measured in port #2. (b) The equivalent RLC resonant circuit of the resonator.

II. MICROWAVE KINETIC INDUCTANCE DETECTORS

When a photon with energy hf is coupled into a superconducting film cooled well below its transition temperature ($T \ll T_c$), the photon breaks Cooper pairs if the energy of the photon is above twice the gap energy of the superconductor ($hf > 2\Delta$). The resulting increase in quasiparticle density changes both the surface inductance and surface resistance of the film. When the film is incorporated in a microwave resonator, the quasiparticles reduce both the resonant frequency and Q (Fig. 2).

Many high- Q resonators can be coupled to a single feedline (Fig. 3). A frequency comb of excitation signals injected in the 'in' port is amplified by a single cryogenic amplifier (usually a high electron mobility transistor, or HEMT). The energy or power in a photon signal coupled into resonator can be inferred by measuring the complex forward transmission S_{21} using a standard homodyne technique (Fig. 4).

Fig. 2. The transmitted microwave signal (S_{21}) of a superconducting microwave resonator before (right, solid black line), and after (left, dashed red line) a photon is absorbed in the film. The increase in quasiparticles reduces the resonant frequency (left-pointing red arrow), and the quality factor (upward red arrow).

The quadrature of the transmitted microwave signal S_{21} associated with the change in resonance frequency (Fig. 2) exhibits significant excess noise from coupling to two-level systems in surface dielectrics [4]. In contrast, the signal associated with a change in resonator Q exhibits no excess noise down to the vacuum noise level [5]. The fundamental limit on noise performance of the dissipation signal is set by the noise of the follow-on amplifier and by quasiparticle generation-recombination noise. At submillimeter and shorter wavelengths, this noise performance can be below the photon shot noise. At millimeter and longer wavelengths, the HEMT noise is typically larger than the photon noise. Quantum-limited microwave amplifiers are needed [5].

Fig. 3. A schematic showing three superconducting microwave resonators coupled to a single feedline, each with a unique resonant frequency. A comb of three excitation tones is summed and inserted into the 'in' port. Each tone is tuned to match the resonant frequency of one of the resonators.

Fig. 4. Electronics to read out a superconducting microwave resonator. A hybrid is used to split a tone at the resonance frequency. One half interacts with the resonator, is amplified, and is inserted in the rf port of an IQ mixer. The second is phase- and amplitude-adjusted, and inserted into the LO port. The resulting I and Q signals from the mixer form a phasor that represents the transmitted signal.

A 2,304-pixel array of MKIDs is now being constructed for submillimeter astronomy. This instrument, MUSIC, will be used for submillimeter surveys at the Caltech Submillimeter Observatory [6]. Since many hundreds of MKIDs can be read out in each amplifier channel, much larger arrays will be constructed for future instruments.

III. SUPERCONDUCTING TRANSITION-EDGE SENSORS

If a photon is coupled into a superconducting film operated within the narrow transition region between the normal and superconducting state, the temperature and thus electrical resistance of the film rises. If the change in resistance is measured, the energy of the photon, or the power in a photon signal, can be inferred. The noise performance, which is limited by thermodynamic energy (or power) fluctuations in the film, can be orders of magnitude better than is achieved using a conventional semiconductor detector [2].

Fig. 5. Photograph of a dissipationless, unshunted rf SQUID coupled to a superconducting microwave resonator. The TES current is applied on the left through a filter that prevents the microwave tone from interacting with the TES. The current from the TES changes the flux in the SQUID. The SQUID couples to a quarter-wave coplanar waveguide resonator on the right.

Fig. 6. A TES (the variable resistor in the figure) is inductively coupled to a SQUID consisting of a superconducting loop interrupted by a single Josephson junction. The inductance of the Josephson junction is a function of the magnetic flux applied to the SQUID, and thus the current through the TES. The SQUID is also inductively coupled to a superconducting resonator. Many high-Q resonators are coupled to a single feedline, and a frequency comb of microwave probe signals is amplified by a single HEMT, allowing a large number of detectors to be multiplexed.

The TES is coupled directly to a superconducting microwave resonator, and the photon signal can be sensed by measuring the change in complex forward transmission S_{21} . However, in that case (as in the case of MKIDs), the noise performance is limited by the noise temperature of the follow-on microwave amplifier. Since the noise temperature on the output of a voltage-biased TES is approximately twice the physical temperature (typically ~ 100 mK), a quantum-limited microwave amplifier is required. As broadband, quantum-limited microwave amplifiers become available, direct coupling of the TES to a resonator will be attractive.

Fig. 7. As the flux through the SQUID changes, the resonance frequency of the resonator shifts. Because of quantum interference, the resonance frequency is a periodic function of the applied flux. For a particular resonator at 5.5 GHz, the measured transmission is shown for a range of applied fluxes between 0 and a half of a flux quantum, which traces out the full range of resonance frequency modulation.

Fig. 8. The phase of the transmitted microwave signal (S_{21}) is plotted against the flux applied to a SQUID coupled to a superconducting microwave resonator operated at 5.5 GHz. The phase angle is periodic with the applied flux with the period of a flux quantum (Φ_0), as is expected from the quantum interference in the SQUID.

However, better results can presently be achieved by coupling the TES to the resonator through a superconducting quantum interference device (SQUID) (Fig. 5), which provides an initial amplification before a follow-on HEMT amplifier. Many high-Q resonators, each coupled to a TES through a SQUID, can be read out using a single feedline (Fig. 6). The best results have been achieved using an unshunted single-junction SQUID [7]. A frequency comb of excitation signals injected in the 'in' port can be amplified by a single HEMT.

As the flux applied by a TES to a SQUID changes, the frequency of the associated resonator shifts (Fig. 7). The

Fig. 9. The use of flux-ramp modulation to linearize the response of the SQUIDs in a superconducting microwave resonator array. The total flux in the SQUID is the sum of a linear flux ramp applied by a flux modulation line, and the flux from the TES coupled to the SQUID. (a) A linear flux ramp is applied to the SQUID as a function of time. The blue (bottom) line is the applied flux in the absence of a from the TES. The green (top) line is the total applied flux in the presence of a flux offset from a slowly varying current from the TES. (b) The flux ramp causes a periodic modulation of the transmitted phase of the complex forward transmission S_{21} . A slowly varying flux signal from the TES causes a temporal shift in this modulating signal (from the blue (left) line in the figure to the green (right) line in the figure).

Fig. 10. The flux from the TES is demodulated from the flux-ramp-modulated signal by measurement of the phase shift. The measured current in an example data set is plotted against the actual current from the TES (blue circles). The red line is the expected response. This data set puts an upper limit on the integral nonlinearity of the demodulated signal of 0.1%.

forward transmission S_{21} is shown for one resonator at 5.5 GHz at different applied fluxes.

If the resonator is excited with a single tone near the resonant frequency, the phase of the transmitted microwave signal varies with the applied flux (Fig. 8). By measuring the phase of this signal, the current flowing through the TES, and thus the photon energy, can be inferred.

The transmitted phase in Fig. 8 is a nonlinear function of the applied flux from the TES. A mechanism is required to linearize this response. While a separate flux feedback signal could be applied to each SQUID to linearize the response, it is undesirable to provide a separate flux feedback wire to each pixel in a large camera. Instead, one common wire is used to apply a flux ramp to all SQUIDs simultaneously (Fig. 9).

The flux from the TES is measured by demodulating the modulated signal shown in Fig. 9 [7]. The measured current is a linear function of the current from the TES (Fig. 10).

Fig. 11. Transmission dips associated with 34 SQUID-coupled resonators on a single feedline. The resonators are uniformly spaced, with the exception of one resonator that was misplaced due to a mask error.

Circuits have been developed that multiplex more than 32 TESs on each feedline (Fig. 11). These devices have been used to read out small arrays of TES detectors incorporated in a cosmic microwave background polarimeter. A large array of CMB polarimeters read out with resonator-coupled TES detectors is now planned.

VII. Conclusion

Superconducting microwave resonators are a critical technology to enable larger arrays of superconducting detectors for next-generation applications. Large arrays of resonators coupled to both MKIDs and TESs are under development. For these technologies to reach their full potential, further development is needed in both broadband, quantum-limited microwave amplifiers, and high-performance digital readout electronics at room temperature.

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