Multiplexed superconducting quantum interference device (SQUID) readout systems are critical for measuring large arrays of superconducting transition-edge sensors (TES). We demonstrate a code-division SQUID multiplexing (CDM) architecture that is modulated by Walsh codes. Measurements and simulations of a prototype multiplexer show that this modulation scheme is not degraded by SQUID-noise aliasing, suppresses parasitic pickup, and has low levels of crosstalk. These properties enable this architecture to scale to large TES arrays. Furthermore, CDM modulation suppresses the $1/f$ knee in the noise to below 20 mHz, suggesting the use of this circuit for low-frequency-noise mitigation in more general SQUID applications. © 2010 American Institute of Physics. [doi:10.1063/1.3378772]
FIG. 1. (Color online) Top: Schematic and photographs of a four-row code-division multiplexer. The dc $\phi_0/2$ flux offset is applied to one of the two SQUID switches in each SPDT switch. The row address lines ($I_1$, $I_2$, $I_3$, $I_4$) then modulate the flux in each SPDT switch by switching between zero or $\phi_0/2$ flux. The result is that one half of the SPDT switch is open, while the other half is closed, so the input signal, $I_{in}$, couples to the summing coil through either $-M$ or $+M$. The row address currents are orthogonal Walsh functions as shown to the left of the schematic. The signals from all SPDT switches are coupled to the SA SQUID amplifier through a summing coil. Room temperature digital-feedback electronics (DFB) are used to servo the feedback current, $I_{fb}$, which keeps the SA output in its linear regime. The second dimension of CDM would come from common row addressing lines for multiple CDM columns (not shown, but similar to TDM). Bottom: Schematic of SPDT integrated with a TES, showing how a dc biased TES can be connected to an SPDT switch with the same components used in TDM systems: A Nyquist inductor, $L_{Nyq}$, to limit the TES bandwidth and a shunt resistor, $R_{sh} \ll R_{TES}$, to provide a hard voltage bias for the TES.

architecture requires only minor firmware modifications to existing room-temperature TDM electronics.

Previous attempts to implement CDM with TESes have switched the polarity of the TES bias line across the SQUID switches, with a higher critical current that approaches zero for $R_N = 2 \, \text{n}\Omega$. The other SQUID switch, with a lower critical current, is used for polarity reversal. This implementation prevents detector-noise aliasing by separating the high-bandwidth switching circuit from the low-pass filtered detector bias circuit. The TES (or other input) current drives it normal, and the TES switch current is reversed from $+M$ to $-M$ by applying an additional $\phi_0/2$ to both SQUID switches via the row-address lines, which interchanges the normal and superconducting states. The readout SQUID is an amplifying series array (SA) of SQUIDs that connects to a room-temperature preamplifier and to digital feedback (DFB) electronics.6

Prototype four-row CDM multiplexers have been fabricated (Fig. 1) and tested in a liquid He dip probe. SA $V-f$ and $I-V$ curves are measured to determine the threshold current of the SQUID $I_{c,\text{max}} = 7.6 \pm 0.2 \, \mu\text{A}$ and the feedback coil mutual inductance $M_{fb} = 26.0 \pm 0.1 \, \text{ph}$, and to estimate the power dissipation for a single column (less than 1 nW). Dissipation in the SQUID switches is predicted to be negligible compared to the SA dissipation and similar to the TES bias power. SQUID switch $I-f$ curves (Fig. 2) are measured by application of a $\phi_0/2$ offset to each of the SQUID switches followed by applying an additional $\phi_0/2$ row-address to switch the polarity of the SPDT. The linear dynamic range of the input in this implementation of CDM is limited by the maximum SQUID switch current critical (Fig. 2). While the prototype circuit described here was designed primarily to test this CDM implementation and is appropriate for use with relatively low-current (less than 6 $\mu\text{A}$) signals, the next generation of CDM chip under development will be designed for higher current applications.

When the readout is multiplexed, the amplified SA output is connected to DFB electronics6 that apply polarity-modulating row-addresses synchronously with interleaved proportional-integral (PI) feedback values for each Walsh frame. Measurements of row-switching settling periods indicate that row-switching rates greater than 1 MHz are possible with this circuit. To facilitate low-frequency noise measurements, a passive $f_{3dB} \approx 200$ kHz filter was used to limit the open-loop bandwidth of the SA output. The four-row multiplexing tests described here were carried out with a 200 kHz switching rate, and thus a 50 kHz frame rate.
To demonstrate the CDM functionality, signal generators were used to apply different signals to all four input lines while multiplexing. Figure 3 shows the raw DBF data for the four Walsh states as well as the decoded data after applying $W^{-1}$ (Eq. (1)) to the raw data. Low-frequency SQUID noise, noise-pickup lines, and the arbitrary dc SQUID offset are all generally confined to the nonswitched row. The multiplexed noise measurements in Fig. 4 were acquired with no signals on the inputs to demonstrate the reduction of all of these effects on the switched rows. The nonswitched row contains a 1/f knee at $-2.2$ Hz as well as parasitic pickup lines at 60 Hz and harmonics, which are consistent with nonmultiplexed measurements of the SQUID noise. The switched rows show no evidence of parasitic pickup or a 1/f knee above 20 mHz. Due to the 200 kHz filter on the output line combined with sparse data sampling after the settling time by the DBF electronics, the measured white noise level of $1.5 \pm 0.04 \mu \Phi_0/\text{Hz}^{1/2}$ is degraded by $0.9 \pm 0.1 \mu \Phi_0/\text{Hz}^{1/2}$; however, there is no SQUID-noise degradation due to increasing the number of rows.

Crosstalk in Walsh space has been simulated and measured by application of sine-wave signals between 1 Hz and 25 kHz to the inputs, and comparing the power spectral densities of the decoded time streams of all rows at the sine-wave frequencies. The measurements and simulations are consistent. After implementing a simple algorithm during decoding to remove linear drift within data frames, we find that crosstalk between all channels is suppressed at 100 (1000) Hz to between $-90$ ($-50$) dB and $-106$ ($-66$) dB for a frame rate of 50 kHz. Measurements of the nonswitched row have larger crosstalk than predicted from the simulations, which is expected, due to parasitic magnetic crosstalk between pixels that is not suppressed in the nonswitched row. In CDM implementations with detectors, this row will be used for characterization of amplifier noise and parasitic pickup and will not be connected to a detector.

We have demonstrated a functional code-division SQUID multiplexer that is not degraded by $\sqrt{N}$ SQUID noise aliasing. Our measurements show that CDM suppresses parasitic pickup and SQUID 1/f in the readout circuit and preclude a 1/f knee above 20 mHz on the switching rows. These qualities make the CDM implementation described here attractive for general SQUID applications with strict noise requirements. In addition, because the rows are switched by use of magnetic flux, future versions of this CDM have the potential to take advantage of binary addressing in which $2^n$ rows are modulated by $n$ addressing lines. Our next generation of CDM chips will include a larger number of rows and will target higher SQUID-switch critical currents and mutual inductances for use with TES.

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