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SQUID-based multiplexing by slope switching and binary-to-Hadamard address translation

Mikko Kiviranta and Nikolai Beev

***Abstract*— We have demonstrated multiplexing and demultiplexing of seven test signals using the Hadamard basis set. The encoding utilizes the sign change of the SQUID gain when a $\Phi_0/2$ flux shift occurs. The periodicity of the SQUID response allows recursive construction of in principle arbitrarily high order Hadamard matrices out of binary addresses and hence makes possible to access *N* channels by $\log_2 N$ address lines.**

***Index Terms*— Code division multiplexing, SQUIDs, Superconducting photodetectors.**

I. INTRODUCTION

THERE IS an infinite number of orthogonal basis sets which could be used in SQUID-based multiplexing of cryogenic detector matrices [1]. When a function taken from the basis set is multiplied with the detector signal, the signal gets 'fingerprinted' so that it can be resolved from the sum of many such signals at the decoding stage. Three basis sets (Fig. 1) provide certain technical advantages and have hence been favored in the past. The time domain basis set (TDM, Fig. 1a) was pioneered at National Institute of Standards and Technology [2]. Because the basis set comprises of two-level functions, the encoding can be performed with a simple on-off cryogenic switch. The main disadvantage of TDM is the noise penalty [3] which keeps degrading the signal-to-noise ratio as the multiplexing factor is increased.

The frequency domain basis set (FDM, Fig. 1b) was originally pursued by Berkeley [4] and by the VTT-SRON collaboration [1, 5]. Because the FDM basis functions are continuous, a continuous cryogenic multiplication is required for encoding. Transition edge sensors (TESes) can function as continuous multipliers via Ohm's law [1], and they tend to work well in the bolometric mode where the TES remains close to the thermal equilibrium. However, in calorimetric mode where non-equilibrium excursions occur, excess noise has been observed [6]. The important advantages of the

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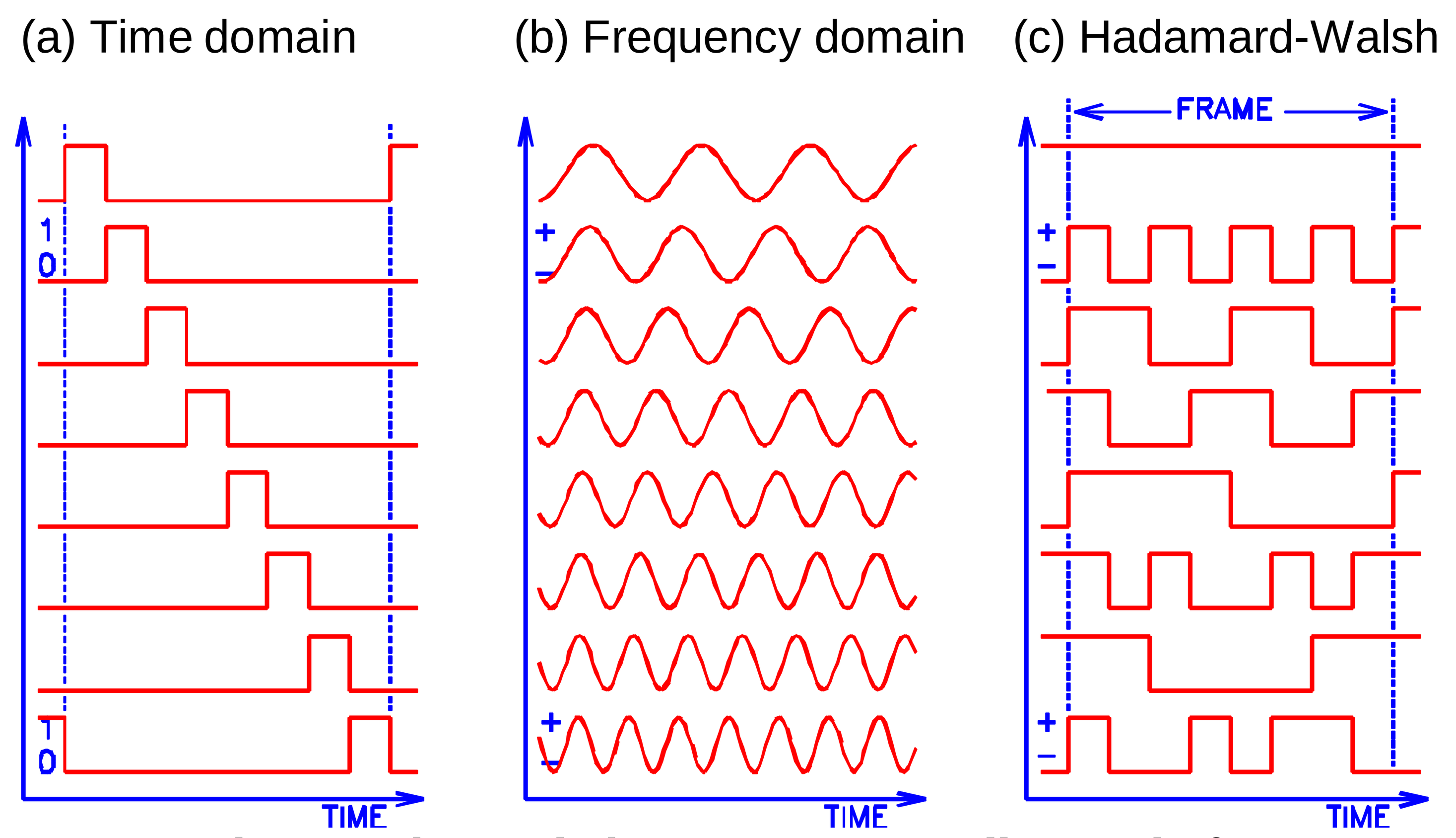

Fig. 1. Three orthogonal basis sets generally used for cryogenic multiplexing.

FDM are related to its compact spectral representation and lack of the dc component in the encoded signals. The consequent possibility of reactive detector biasing and non-galvanic signal coupling helps in reducing the heat generation which is important when the cooling budget is limited, e.g. in the SAFARI instrument [7]. 1/f noise of the amplifiers is also avoided, because there is no dc- or low-frequency component present in the modulated signal.

The third, Hadamard or code domain (CDM, Fig. 1c) basis set was proposed in [8] and demonstrated in practice at NIST [9], [10]. The CDM basis functions are two-level and thus allow encoding by commutating (on-on) cryogenic switches. When the lowest-order modulating function is discarded, the remaining signals lack the dc component and many of the advantages of the FDM become applicable. Equivalently with the TDM case [2], detector signals should be low pass filtered before encoding so that the random component of each signal, i.e. noise, does not change appreciably during the frame time (Fig. 1c). With this provision, also the random component can be resolved into different channels in the demodulation step, and noise aliasing does not occur.

One important feature of the CDM approach is the possibility to implement binary addressing by utilizing the flux response periodicity of quantum interferometers, as suggested in [9]. To our knowledge, the present paper describes the first SQUID-based practical demonstration of binary addressing.

Binary addressing is a very powerful method: for example, readout of a 16 384 –pixel detector array would only require 14 address lines, while in the

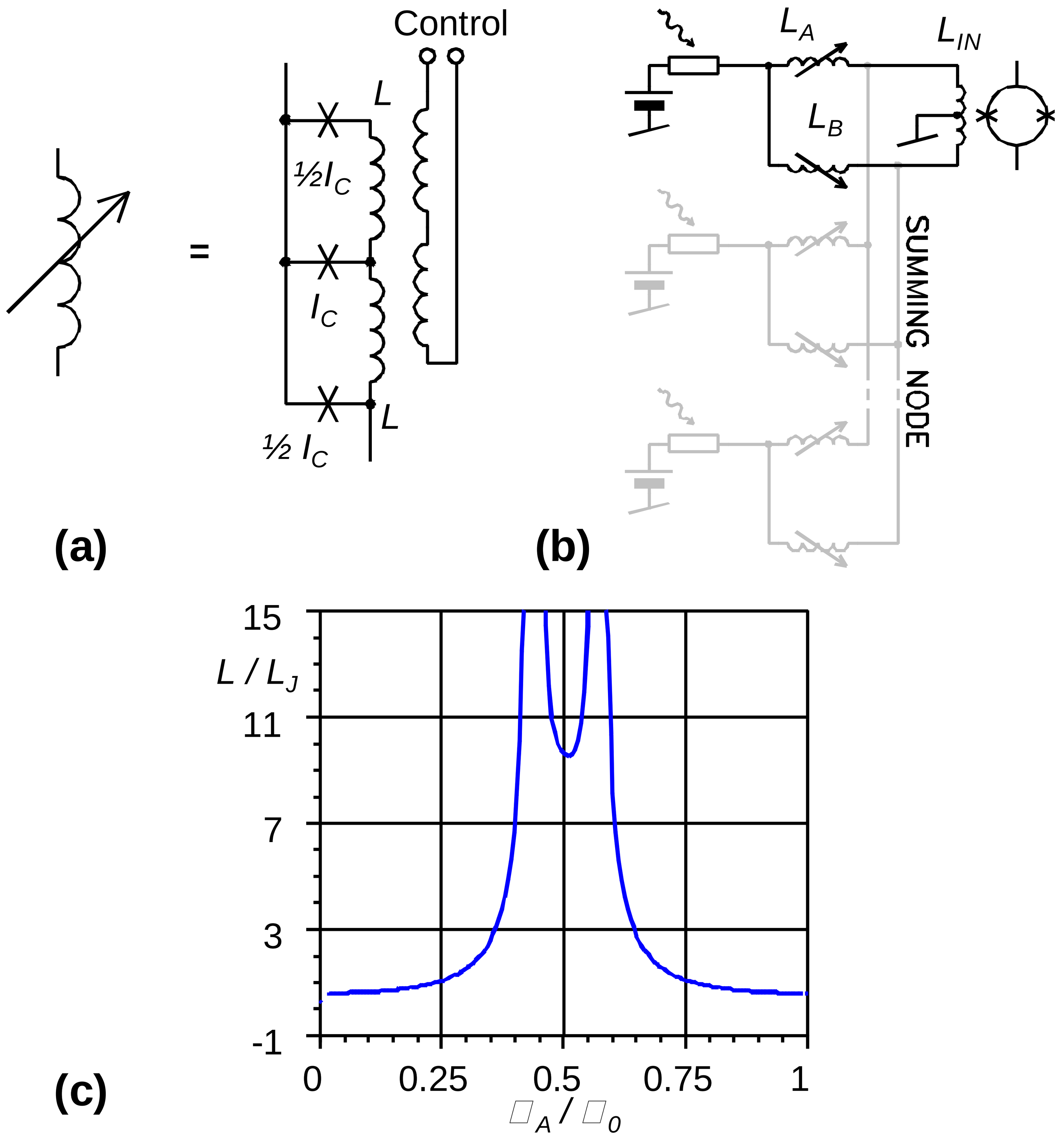

Fig. 2. (a) The 3-junction Zappe interferometer as a flux-controlled adjustable inductor. (b) Inductive divider as a commutating switch: in one polarity the inductance L_A is small and L_B is large, driving the TES current through positively oriented half of the SQUID input coil. In the other polarity L_A is large and L_B is small. (c) Small-signal inductance of a Zappe interferometer as a function of applied flux when $\Phi_0 / I_C L = 30$, expressed in terms of Josephson inductance $L_J = \Phi_0 / (2\pi I_C)$.

standard TDM [2] approach 128 address lines would be needed. The 16 384 pixel encoding would only involve the maximal flux shift of 7 periods in the encoding SQUIDs, which is quite feasible.

II. Implementation of CDM switches

One can implement the commutating switches conveniently by Josephson junctions (JJs). When JJs are operated in voltage state, they typically must be shunted resistively in order to avoid hysteresis. The shunt resistance would inject wideband Johnson noise to the summing node (Fig. 2b), which would cause the noise floor of a N-pixel readout to increase $\sim N^{1/2}$. It is more attractive to use the JJs in the superconducting state where shunt resistance is only needed to damp plasma oscillations and its value can be much larger.

We have studied recently three-junction Zappe interferometers [12] (Fig. 2a) whose use in this application we learned from [13]. Compared with the dc SQUID in the superconducting state, the Zappe interferometer has a wider flux range where its inductance is large (Fig. 2c). When dimensioning the switch, the chosen JJ critical current must be larger than the maximum signal current $I_C > I_{TES}$, which implies a small switch inductance L_A , $L_B \sim L_J = \Phi_0 / (2\pi I_C)$. The

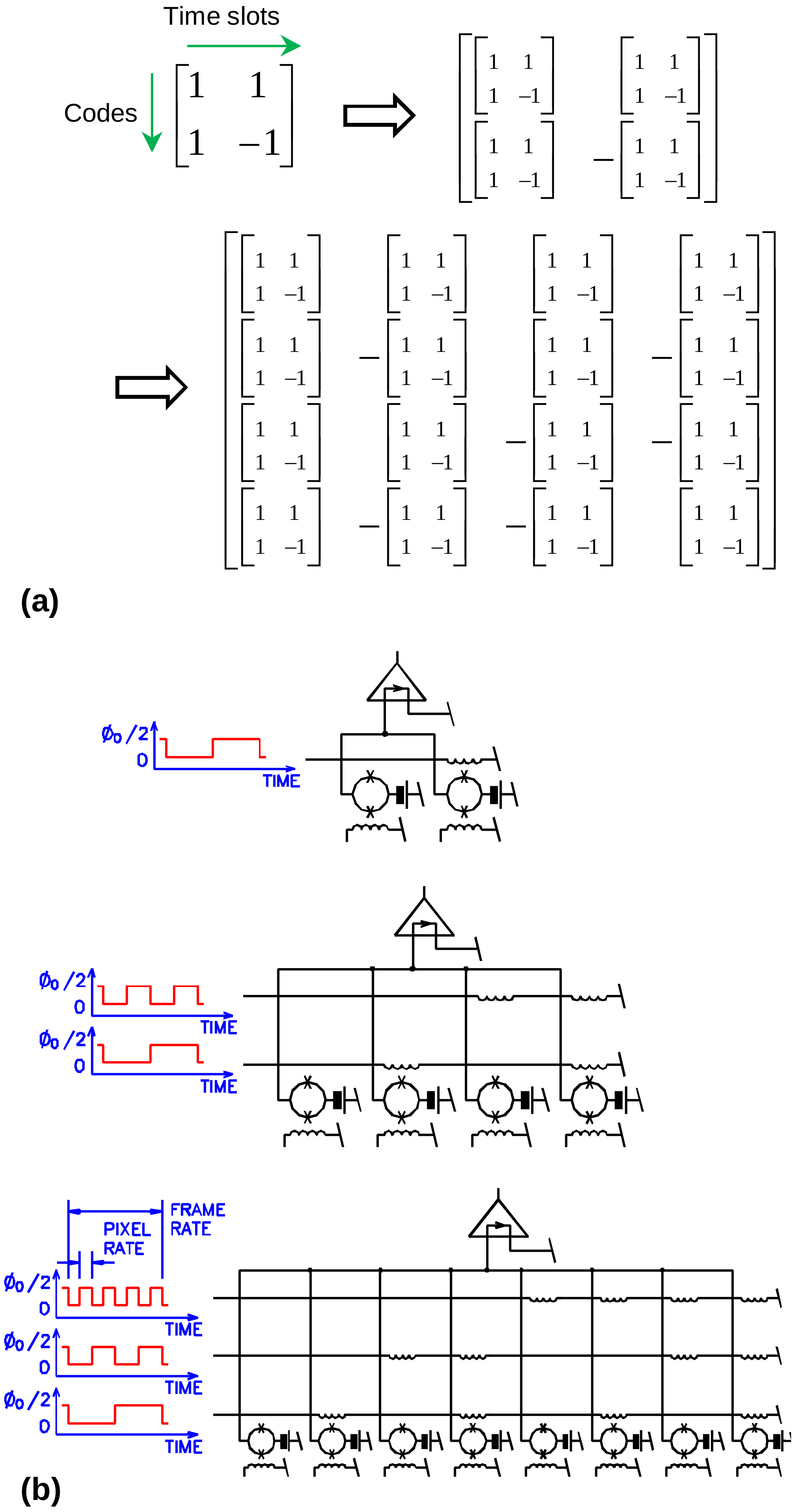

Fig. 3. (a) Hadamard matrices can be generated by taking the primitive 2 x 2 matrix and by recursively replacing its elements with copies of the primitive matrix. In the multiplexing context the rows correspond to signal channels and columns correspond to time slots. (b) The recursive procedure is equivalent to repeated doubling of the primitive 2-SQUID cell when an additional double-rate $\Phi_0/2$ flux shift is summed to the lower half of the new cell.

switch must dominate over the input inductance of the amplifier SQUID for current steering to occur: L_A , L_B >> L_{IN}. Because the current noise floor is set by the SQUID energy resolution $i_N = (\varepsilon / 2 L_{IN})^{1/2}$, one needs to couple several interferometers in series in order to reach a reasonable dynamic range I_{TES} / i_N.

We have fabricated current steering switches, whose each branch contains 10 Zappe interferometers in series. The dynamics of the system turned out to be very complex, however, and those switches are unsuitable for practical use. Therefore we resorted to a simpler approach to demonstrate the binary-to-Hadamard code translation, which utilizes the fact that the gain polarity of a dc SQUID amplifier changes when a Φ_0 /2 flux shift is applied. The dc SQUIDs are run in voltage mode, which unfortunately leads to the ~$N^{1/2}$ noise penalty. The penalty is caused by the output current noise of each SQUIDs getting injected to the summing node (Fig. 4) non-fingerprinted.

III. The Slope Switching Experiment

In the experiment we performed the signal encoding by switching seven readout SQUIDs between the positive and negative slopes of the flux response. The experiment utilized the mechanism, hinted at by Irwin et. al. [9], that successive multiplications by -1 inherent in the construction of Hadamard matrices can be replaced by successive summations of Φ_0/2 flux shifts, see Fig. 3. This enables one to use ordinary binary code when addressing the SQUIDs.

For the experiment, we built a module out of four chips each containing two 60-series SQUID arrays [11]. The arrays were read out by a simple transconductance amplifier built around an AD797 operational amplifier. The opamp creates an cryogenic virtual ground (Fig. 4) into which the SQUID currents are summed. SQUIDs are voltage biased by a forced potential difference between the inverting and non-inverting inputs of the opamp. Addresses were created by a simple CMOS binary counter. The opamp output was Nyquist filtered with 150 kHz corner frequency and digitized by a National Instruments USB-6363 acquisition unit. The SQUID module was immersed in LHe and magnetically shielded by a Pb + Cryoperm can. We relied on flux trap resistance of the SQUIDs [11] which allowed us to use one flux setpoint line common to the 7 channels. The SQUIDs were driven from seven sawtooth wave generators, constructed out of simple CMOS Schmitt triggers. The ± 2.5 $\mu A_{p\text{-}p}$ amplitude triangle waves whose frequencies ranged from 0.25 Hz to 4 Hz were fed to the SQUID input coils, encoded, digitized and decoded. The waveforms are shown in Fig. 5, when decoded with the uncorrected ideal Hadamard matrix. At high frame rates the system begins to suffer from glitches related with the binary address transitions (Fig. 5a). We believe the glitches are due to ground bounce in our particular setup. The input-referred noise floor was 15 pA/Hz$^{1/2}$ which roughly equals the expected opamp-dominated, $N^{1/2}$ – enhanced SQUID noise.

Another set of signals was produced by a set of two-level burst generators, which were devised for the purpose of measuring the true encoding matrix. These test signals, shown in Fig. 5c, give an indication of the performance of the uncalibrated system. In particular, channel-to-channel crosstalk of ±15% is evident in the zeroth channel, which can be explained by critical current variation in the encoding SQUIDs, which we had found to be significant in this [11] fabrication batch. Such variation leads to non-ideal encoding matrix, as the gain in different channels varies and the matrix entries differ from unity. Improved crosstalk should be obtainable if decoding took place by true inverse of the encoding matrix, rather than by the ideal Hadamard matrix. However, true decoding was not implemented in the experiment at hand.

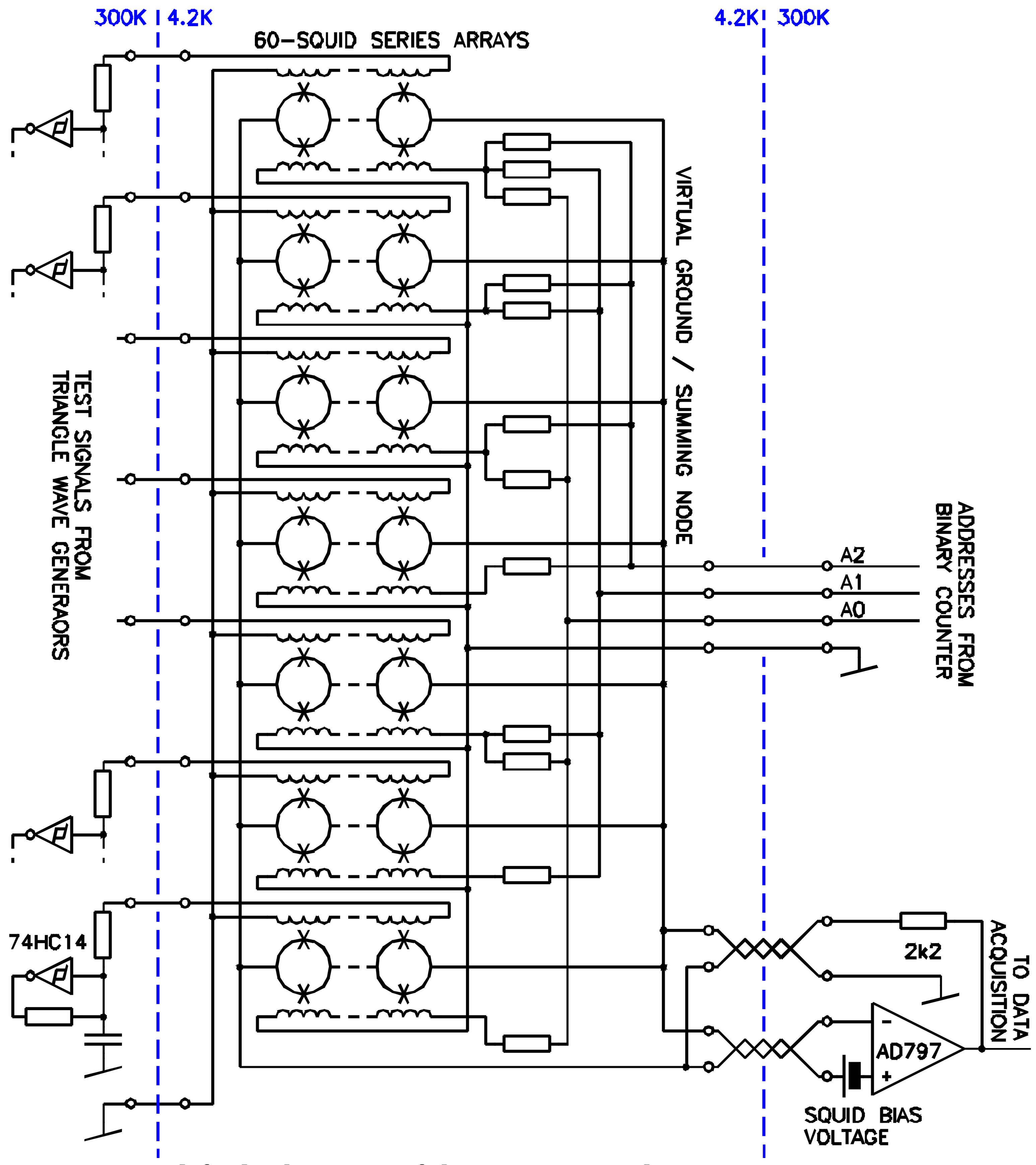

Fig. 4. Simplified schematic of the experimental setup.

IV. Conclusion

We have demonstrated that the SQUID slope switching is a feasible way to multiplex current signals at cryogenic temperatures. We have further demonstrated that significant reduction in the number of address lines in such a multiplexer is possible if binary-to-Hadamard address translation is applied.

We consider the use of superconductive-mode current steering switches as the baseline approach, and the slope-switching approach merely a demonstration. Still, the $N^{1/2}$ -proportional noise penalty in slope switched CDM is no worse than the penalty in the TDM [3]. Hence the slope switching may find use in niche cases where a very large number of moderately noisy

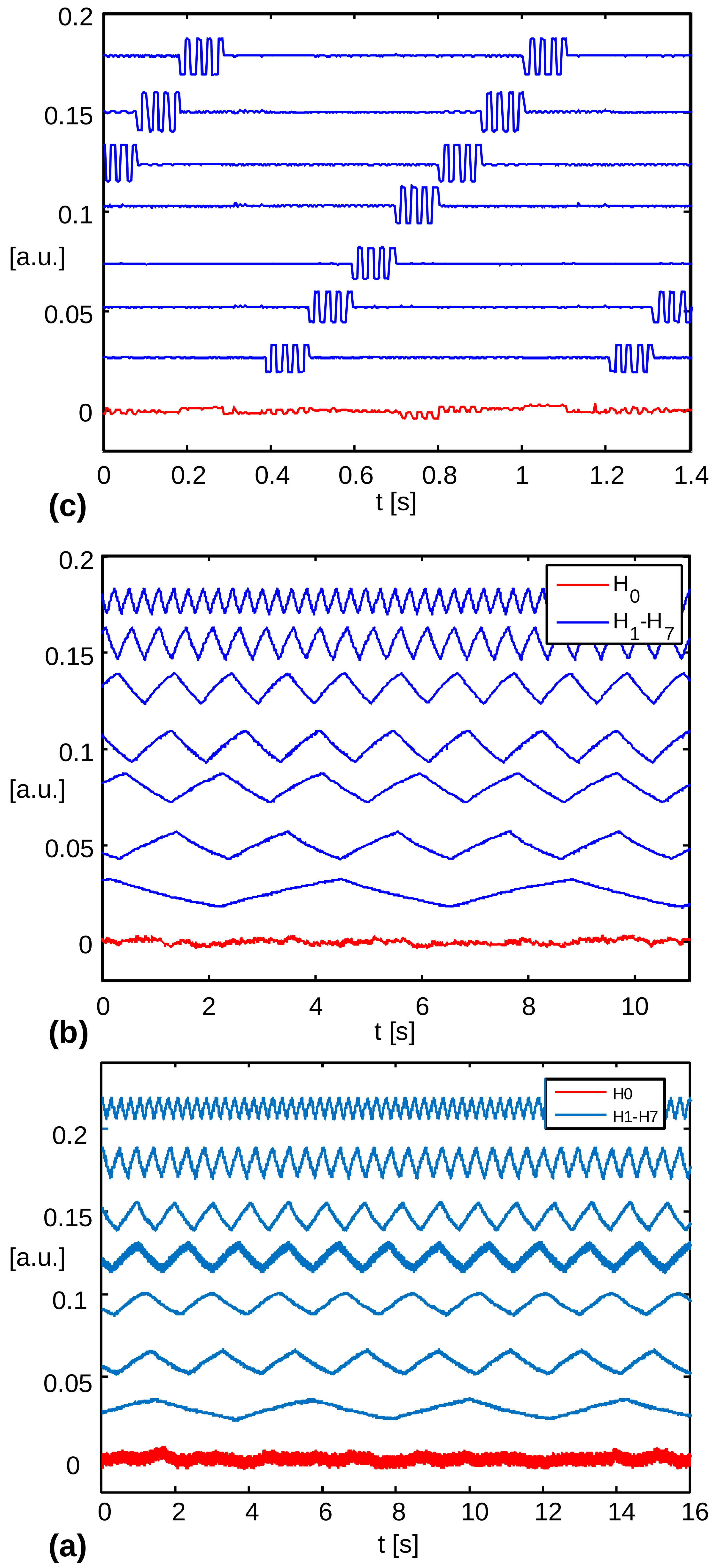

Fig. 5. Encoded, digitized and decoded test signals: triangle wave signals encoded (a) at 3900 frames per second and (b) at 310 frames per second, and (c) two-level calibration bursts encoded at 310 frames per second. Arbitrary units are used in the vertical axis. There is no SQUID-encoded signal in the H0 channel although it is decoded and included in the plots. Decoding was performed by the ideal Hadamard matrix rather than by inverse of the true encoding matrix.

cryogenic detectors must be multiplexed.

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