A Frequency Division Multiplexing Room-temperature Electronics Readout Scheme for TES Calorimeter Arrays

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Abstract—**With the progress of material science and thin film preparation technology, the Transition-Edge Sensor (TES) detector-related technologies have been rapidly developed. The TES detector arrays find extensive applications in high-energy physics and nuclear radiation detection. The Frequency Division Multiplexing (FDM) technology is one of the mainstream multiplexing technologies used in TES readout that reduces thermal load. This paper presents the principle of the TES for applications in astrophysics and particle physics. Then, it proposes a room-temperature electronics readout scheme for the FDM readout system of the TES arrays. This scheme enables precise adjustment of the 40-channel TES bias signals so that the TES arrays can operate at the set optimal operating frequency. This scheme achieves high-precision amplification, sampling, processing, and feedback of TES signals. In the feedback algorithm, the logic resources of FPGA are used to achieve accurate phase compensation.**

Keywords—TES, FDM, Readout Electronics

I. INTRODUCTION

TES is one of the most critical core components of ultra-high-resolution detectors and has broad application prospects [1]. Its successful development is of great significance for constructing high-resolution and high-sensitivity particle detection systems with the development of science and the advancement of manufacturing processes. Owing to the ultra-high temperature sensitivity, large arrays of TES microcalorimeters have been used in space-based and ground-based experiments within the fields of astrophysics and particle physics. The detector comprises an absorber, a TES-based thermometer, and a thermal bath. When operating as a calorimeter, TES is weakly coupled to a thermal bath at a temperature lower than the TES critical temperature and well coupled to an absorber.

TES is actually a superconducting film that can be self-heated and stably maintained in the transition state by means of an AC or DC bias circuit, acting as a thermometer[2]. Its resistance changes sharply with temperature. As illustrated in Fig.1, assuming the heat capacity of the absorber is C_e , when a particle with energy E_p is incident and absorbed, the temperature of the absorber will increase by $\Delta T = E_p / C_e$, leading to a corresponding change in the resistance of the TES, denoted as ΔR. Under the action of the bias circuit, changes in the TES resistance ΔR will cause changes in the branch current ΔI. Then the branch current, which contains particle signal, is amplified by superconducting quantum interference devices (SQUID) and processed by the room temperature readout circuit. In this way, the TES detector achieves high-precision detection of incident particle energy.

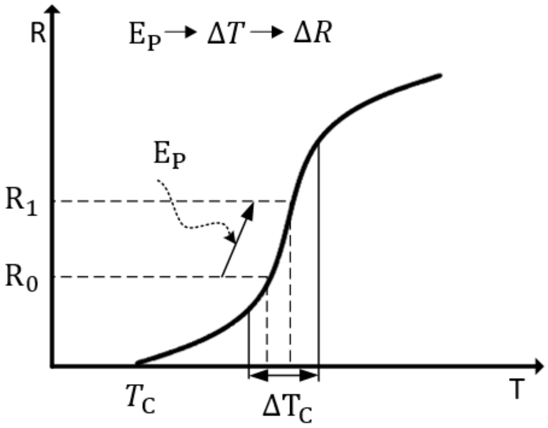

Fig.1. Resistance changes of TES after absorbing energy E_p. T_C is the superconducting critical temperature, ΔT_C is the superconducting transition width.

For excellent spectral performance, microcalorimeter arrays typically operate at subkelvin temperatures. Consequently, the number of thermal loads that connect the cryogenic calorimeter to the room-temperature electronics must be strictly limited[4]. In such a scenario, it is desirable to multiplex several signals onto a reduced number of wires. The readout scheme of large-scale TES detector arrays has always been a hot research topic. A suitable readout solution can effectively reduce system complexity, ensure signal quality, and reduce cost and power consumption. There are currently four mainstream readout solutions: Time Division Multiplexing (TDM), Code Division Multiplexing (CDM), Frequency Division Multiplexing (FDM) and Microwave SQUID Multiplexing (μMUX)[3].

This paper concerns room-temperature electronics readout design for frequency division multiplexing scheme. In the frequency division multiplexing scheme, each TES detector is connected to a passive LC filter and biased with an alternating current at MHz frequency. To avoid crosstalk between adjacent resonators, the resonant frequency of each resonator is separated by a specific frequency, such as 100kHz, and the quality factor Q of the resonant circuit is also as high as possible.

II. PRINCIPLE AND ANALYSIS

Room-temperature circuits include room-temperature low noise amplifiers and room-temperature control circuits. This paper mainly researches the room temperature control circuit based on the existing low noise amplifiers (LNA). The functions of the control circuit are: 1. Provide bias current for the TES array, 2. Provide DC bias voltage for SQUID, 3. High-precision readout of the TES and SQUID array signal, 4. Provide high-precision feedback to the TES array at the same time.

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The voltage bias source generates sinusoids at the resonance frequencies of each LC filter, but each filter only receives its own “carrier” sinusoid, as the remaining ones are filtered out[4]. The voltage source produces a linear superposition of individual carriers, which only require a single wire to transmit these from the room-temperature electronics to the cold stage. The carrier frequencies are chosen in the range between 1MHz and 5MHz. The resonant frequencies of adjacent LC filters are separated by 100kHz.The majority of that limited range is devoted not to sensing the perturbations we are interested in but to the swings of the carrier sinusoids. If only implemented in this way, the SQUIDs would saturate at low multiplexing factors[5]. The solution is to insert a “nuller” signal at the input of the SQUID, performing as the baseband feedback (BBFB) to increase the SQUID's dynamic range and reduce the SQUID's input impedance.

The range of the LNA output signal is 10mA-300mA, and the frequency range is 1MHz-5MHz. A low-pass filter (LPF) should be added to the LNA output to minimize the impact of high-frequency noise. After filtering, amplifying the signal again is necessary to improve accuracy and facilitate sampling.

III. DESIGN AND DESCRIPTION

Fig. 2 shows a simplified schematic of an FDM warm electronics readout system. The LPF consists of a second-order passive RC low-pass filter and an operational amplifier. The passband width can be flexibly adjusted by changing the value of the time constant τ. After filtering, the signal passes through a buffer to convert the single-ended signal into a differential signal. The A/D converter (ADC) is a low-noise 18-bit 65 MSPS high-speed ADC. In the current design, the gain is ten to adapt to the ADC differential full-scale input 3.2V. It should be noted that the amplification factor can be flexibly adjusted by changing the resistor value.

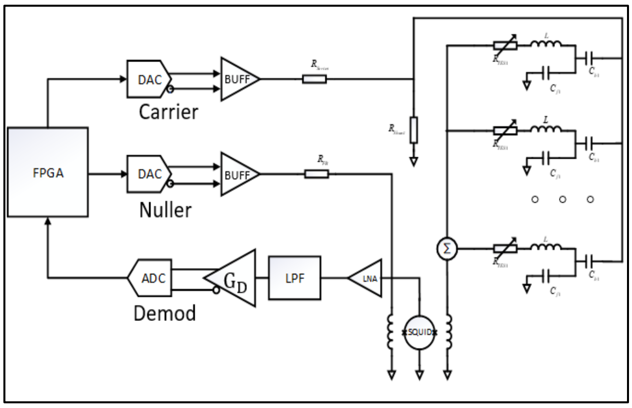

Fig. 2. Simplified schematic of an FDM warm electronics multiplexing 40 TES detectors on a single set of cryogenic wires.

Both “Nuller” and “Carrier” signals are generated by 16-bit 50 MSPS D/A converters (DACs). In the path of “Nuller”, the value of R_{FB} is about 10K ohms. In this case, the output accuracy is about 3nA. In the path of “Carrier”, the value of the voltage dividing resistor is about several thousand ohms. The shunt resistor is located at the cold stage and has a value of 100 milliohms. The FDM modulator and demodulator logic are implemented on a Xilinx field programmable gate array (FPGA).

Fig. 3 shows the simplified diagram of the modulator and demodulator logic in FPGA. Each signal is mixed with 40 reference waveforms. The frequency and the phase of the reference waveforms can be programmed independently.

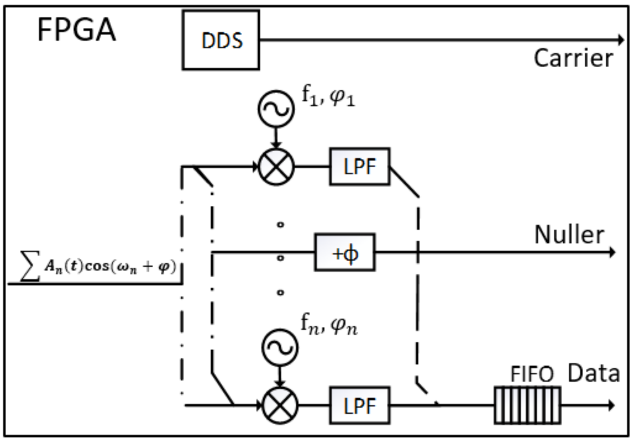

Fig. 3. The simplified diagram of the modulator and demodulator logic in FPGA

In order to get the amplitude of sinusoidal signals at each frequency, it is necessary to consider a phase-dependent DC component produced when two signals of equal frequency are mixed. By adjusting the phase of the reference waveform, the maximum value obtained represents the amplitude of the input signal at that particular frequency. Each LPF is designed to eliminate high-frequency components. Obviously, in order to obtain accurate amplitude values, the phase width of the direct digital synthesizers (DDSs) that generate the reference waveform needs to be as large as possible.

The carrier frequencies are chosen between 1MHz and 5MHz. They are generated directly by DDSs in FPGA. The nuller signal is a fixed duplicate of the multiplexed waveform; at the SQUID input end, they are 180 degrees out of phase.

IV. SUMMARY

This research introduces an FDM room-temperature electronics readout scheme for the TES detector arrays. The carrier frequencies are in the range between 1MHz and 5MHz. A single cryogenic wire can multiplexed readout 40 TES detectors.

V. REFERENCES

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