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Frequency domain multiplexing of pulse mode radiation detectors

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ABSTRACT

The capability to multiplex scintillation detectors or other pulse mode radiation detectors is necessary in some applications where a large number of detectors is required. Frequency domain multiplexing has been previously implemented for applications in astronomy using amplitude modulation on radiation detectors such as transition-edge sensors. We propose an alternative method for multiplexing pulse mode radiation detectors in the frequency domain using convolution. We pass the detector signal to a resonator circuit that converts a detector pulse to a damped sinusoid of a specific frequency which gives a unique tag to the detector. We have developed a prototype frequency-domain multiplexed system for four EJ-309 organic scintillator detectors using four resonators of unique frequencies. The resonator outputs are combined using a fan-in circuit which is then connected to a single digitizer input. Using this system, we demonstrate that the charge collected under the original anode pulse can be estimated from the power spectrum of the damped sinusoid with a relative uncertainty of about 2%. The time-of-arrival of the anode pulse can be estimated using constant fraction discrimination applied to the leading edge of the damped sinusoid with an uncertainty of about 450 ps. We also used a $CeBr_3$ detector to test the performance of our system for spectroscopic applications and found only small degradation in the resolution for a multiplexed detector.

1. Introduction

Frequency-domain multiplexing (FDM) is a technique to combine multiple detector signals into a single output channel to reduce the cost and complexity of the readout electronics. Previously, FDM of radiation detectors has been implemented using large arrays of transition-edge sensor (TES) bolometers/calorimeters [1]. The TES arrays operate at sub-Kelvin temperatures. FDM helps to reduce the heat load associated with large number of wires connecting the cryogenic hardware to room-temperature electronics. Most of the applications of frequency-domain multiplexing in radiation detection are found in X-ray or far-IR astronomy studies [2–4]. Sometimes a bulk Sn absorber is attached to each sensor to increase the detection efficiency for low energy gamma-rays [5]. This method of multiplexing is performed by modulating the amplitude of the carrier signals with the TES signals.

In an FDM readout system with TES bolometers [6], a set of carriers of different frequencies is sent into the system. Each TES allows a single carrier frequency to pass through it, and the TES signal amplitude modulates its carrier frequency. These amplitude modulated carriers are summed into a single channel and then demodulated to recover the individual sensor signals.

This technique of amplitude modulation of each carrier frequency is not feasible with pulse mode nuclear radiation detectors because the detector signal consists of current impulses. Instead, we propose to use convolution [7] as a new way to approach FDM of pulse mode detector signals (shown in Fig. 1). Our method employs a resonator circuit whose impulse response is a damped sinusoid. The pulses from the radiation detector act as input to this circuit, and the frequency of the resonator output gives a unique tag to each detector. All the detectors to be multiplexed are connected to the resonator circuits with different oscillation frequencies respectively. If one of the multiplexed detectors has an event, the resulting damped sinusoid of a particular frequency is passed onto a single digitizer channel using a fan-in circuit. This sinusoidal output is digitized and analyzed in the frequency domain to recover the detector number, the charge collected and the time-of-arrival of the original detector pulse. The detector number is identified by the resonator output frequency while the charge collected is estimated from the sinusoidal amplitude. The time-of-arrival can be estimated from the sinusoidal phase or from constant fraction discrimination applied to the resonator output. This method is intended for applications where only one of the multiplexed detectors is expected to fire in a particular record length of digitized data.

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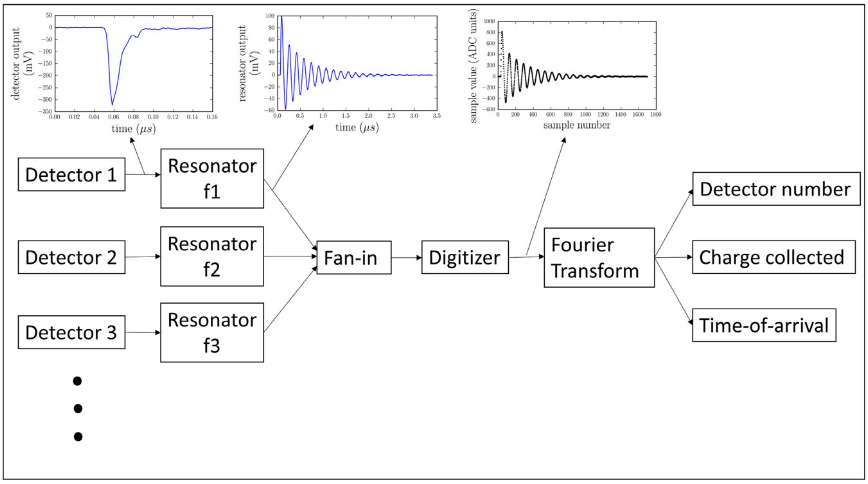

Fig. 1. Block diagram of a frequency-domain multiplexed system.

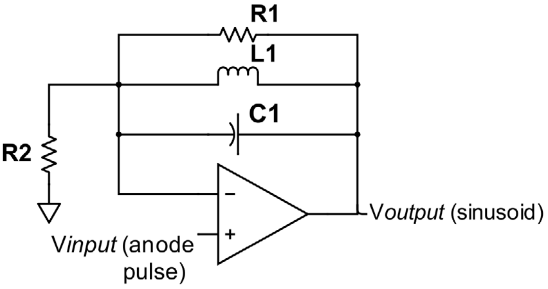

Fig. 2. The resonator circuit.

2. Circuits

2.1. Resonator circuit

The resonator circuit, shown in Fig. 2, is a parallel RLC circuit connected as a negative feedback to an operational amplifier in non-inverting configuration. It is a linear time-invariant (LTI) system described by a linear second-order differential equation that exhibits oscillatory behavior. The impulse response of the circuit is an underdamped sinusoid, given by [8]

$$V_{out} \propto e^{\frac{-w_{LC}t}{2Q}} \sin\left(w_T t + \Phi\right) \tag{1}$$

where $Q = R_1\sqrt{\frac{C_1}{L_1}}$, $w_{LC} = \frac{1}{\sqrt{L_1 C_1}}$, $w_T = w_{LC}\sqrt{1 - \frac{1}{4Q^2}}$ and Φ depends on the initial conditions. The Q factor dictates the decay time of the damped sinusoid and $f_T = \frac{w_T}{2\pi}$ is the frequency of oscillation.

The amplitude of the sinusoid decays to approximately 4% of its original value in Q cycles of oscillation. A large Q results in $f_T \approx \frac{w_{LC}}{2\pi} = \frac{1}{2\pi\sqrt{L_1 C_1}}$; so L_1 and C_1 determine the frequency of oscillation. The value of R_1 determines the Q factor for fixed L_1 and C_1. The transfer function of the non-inverting amplifier, defined as the ratio of the Fourier transform of the output to the input with zero initial conditions, is given by

$$H(w) = \frac{V_{out}(w)}{V_{in}(w)} = 1 + \frac{\frac{Z_{LC}}{R_2}}{j\left(\frac{w}{w_{LC}} - \frac{w_{LC}}{w}\right) + \frac{1}{Q}} \tag{2}$$

where $Z_{LC} = \sqrt{\frac{L_1}{C_1}}$. The transfer function has a maximum gain of $\left(1 + \frac{R_1}{R_2}\right)$ with a phase of zero at resonant frequency $f_T \approx \frac{w_{LC}}{2\pi}$ due to the non-inverting configuration. The bandwidth $BW = \frac{w_{LC}}{2\pi Q}$, is the difference between the half power frequencies. The half power occurs at the frequencies for which the amplitude of the output voltage equals $1/\sqrt{(2)}$ of its maximum.

Four resonator prototypes were designed and fabricated. We used ceramic capacitors (C_1) and inductors (L_1) with values chosen to keep the resonant frequencies between 6 and 15 MHz. The values of the feedback resistors (R_1) were chosen to keep the Q factor between 10 and 15. This gave a sinusoidal decay time of less than 2.5 μs and BW < 2 MHz to all the resonators. With resonator bandwidths of less than 2 MHz, we chose a difference of about 2 MHz between adjacent resonant frequencies to be able to distinguish them from one another. The value of R_2 was 50 ohm for all the circuits.

The LM6171, a high speed operational amplifier with a wide unity-gain-bandwidth product of 100 MHz, was chosen for the resonator circuit [9]. Both negative and positive power supplies were bypassed by ceramic and tantalum capacitors to provide low power supply impedance across a wide frequency range. These capacitors were placed within a centimeter of the power supply pins of LM6171 to ensure that the current was instantaneously supplied to the LM6171 by reducing the inductance in the path of the supply current.

Each EJ-309 detector was connected to a resonator input via a 50-ohm cable. The resonator circuit also has a pass-through for the anode signal to enable simultaneous digitization of a detector pulse and the damped sinusoidal output. During the multiplexing operation, the pass-through is terminated by a 50 ohm shunt resistor to make the device input impedance equal to the characteristic impedance of the cable. The effective output impedance of the LM6171 is 13 ohms, therefore, the LM6171 output has been connected to a 37 ohm resistor to set the output resistance of the resonator at 50 ohm. The resonator output was then connected to the input of the fan-in circuit via a 50 ohm cable.

2.2. Fan-in circuit

The fan-in circuit is a summing configuration that combines the incoming sinusoidal waveforms into a single output channel. A voltage adder circuit with a gain of 2 was used in an inverting configuration using an LM6171. The circuit shown in Fig. 3 combines four damped sinusoids into a single channel.

Each resonator output acts as an input to one of the channels of the fan-in circuit. All the input channels of the fan-in circuit have been terminated by a 50 ohm shunt resistor to reduce the signal reflections. The LM6171 output was connected to a 37 ohm resistor to make the output resistance of the fan-in 50 ohm. The output of the fan-in circuit was connected to a digitizer via a 50 ohm cable.