Biasing Scheme for AC Coupled Strip Detectors

V. T. Jordanov[1], J. R. Macri[2] and M. L. Mayer[2]
[1] Amptek Inc., 6 De Angelo Drive, Bedford, MA. 01730
[2] Space Science Center, University of New Hampshire, Durham, NH 03824

Abstract

A new biasing scheme for ac coupled strip detectors has been developed. Application of this scheme reduces the potential non-uniformity due to variations in the strip leakage currents. The circuit comprises an error amplifier that senses the strip current and compensates for the voltage drop across the biasing resistor. The error amplifier is powered by floating power supplies referenced to the bias voltage. A circuit was built that uses a low power amplifier with femtoamp inputs. The circuit regulates the strip potential to within few mV of the bias voltage for strip currents between 0 and 5 nA with a 1.2GΩ biasing resistor. The circuit has been tested with a CZT strip detector.

I. INTRODUCTION

Recent studies of CZT strip detectors operating at room temperature, indicate irregularities in the strip boundaries and variations of the effective strip width [1, 2]. It has been demonstrated [1] that material non-uniformity is the most probable cause for these observations. This is particularly true for the anode strips when the X-ray interactions are restricted to the region near the cathode surface. In this case, the carriers (electrons) must traverse nearly the full thickness of the material before collection by the anode strips. Differential strip bias is, however, a factor [2] for both anode and cathodes for interactions occurring at all depths. This factor will become more important as more uniform detector material become available and strip detectors are used to address more demanding spatial resolution measurement requirements.

For ac coupled strip detectors, the strip bias voltage is traditionally applied through a high value biasing resistor. Fig. 1 shows a typical strip detector configuration. The strips on either side of the detector are biased from a common voltage source. The strips on the bottom side are biased from voltage source v_b. The voltage at a given strip is equal to the bias voltage minus the voltage drop across the biasing resistor $v_b - i_s \cdot R_b$, where i_s and R_b are the strip current and the biasing resistor respectively. At room temperature the CZT detector strip leakage current is typically on the order of a few nanoampers. This leakage current may produce voltage drop of few volts across 1 GΩ bias resistor.

A particular strip current is due to both the leakage current and the average signal current of that strip. Strip current may vary from strip to strip because of non-homogeneous detector material or differences in strip contact area. As a result, the potential may also vary from strip to strip creating more favorable conditions to collect charge on some of the strips than others. In order to eliminate the differential bias between the strips a bias control circuit was developed that also allows further investigation of this effect.

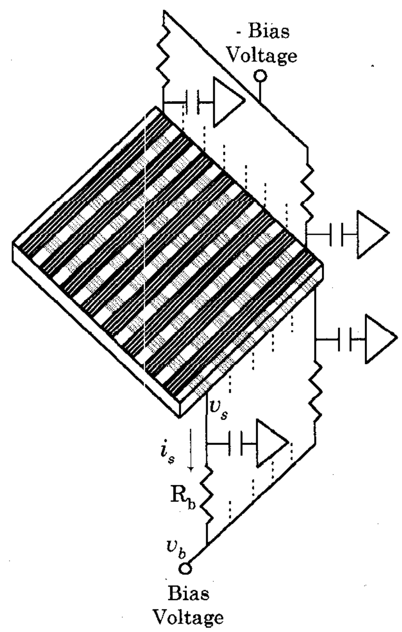


Fig. 1. Biasing scheme of strip detector.

II. BIAS CONTROL CIRCUIT

The circuit that will regulate the strip bias voltage should provide a high impedance at the connecting point to the strip. A common practice to stabilize a dc voltage at a circuit node that may sink or source a current is to use an operational amplifier with negative feedback. Fig.2a shows a simple example of such a circuit.

The operational amplifier A is powered by two floating power supplies (batteries) that are referenced to the desired strip bias potential. These power supplies limit the output voltage range of the amplifier A. Further in the text it is assumed that the bias control circuits are powered using that powering scheme. The non-inverting input of the amplifier A is connected to bias voltage v_b, while the inverting input is

0018-9499/98$10.00

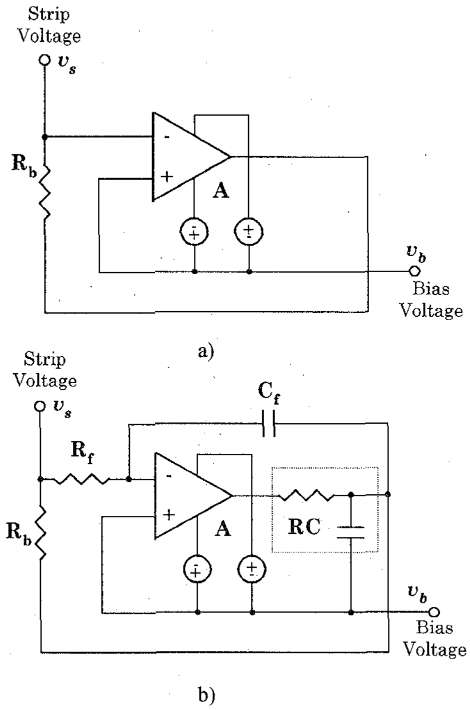


Fig.2. Circuits for regulating the strip bias voltage.

connected to the detector strip. The negative feedback is accomplished via bias resistor R_b. If the amplifier gain is very large (10^5 to 10^6), the input leakage current is very low (pA, fA), and the input offset voltage is negligible (< 1mV), then the voltage at the inverting input will be almost the same as v_b regardless of the current flowing through R_b. This statement holds only if the voltage drop across R_b is less than the output voltage range of the operational amplifier A.

The circuit in Fig. 2a is very simple but has a few drawbacks that affect the signal to noise ratio in the strip pulse processing network. First, the input capacitance of the inverting input is directly coupled to the preamplifier input (in parallel with the strip capacitance) and second, the amplifier A output noise is applied through resistor R_b to the input of the strip preamplifier. In addition, it is necessary to reduce the bandwidth of the amplifier A to avoid possible interference with the strip charge sensitive preamplifier.

The circuit in Fig. 2b solves some of the problems associated with the circuit in Fig. 2a. The strip voltage is monitored through a high value resistor. A feedback capacitor and RC filter have been added in order to reduce the amplifier bandwidth, to improve stability, and to minimize the noise contribution of the amplifier. From the noise point of view, however, the equivalent bias resistor is reduced (R_f is AC terminated through C_f and the amplifier input capacitance). If the factor R_f/R_b is large enough (5 to 10), the noise contribution of R_f diminishes. In such a case, special care must be taken to avoid dc error due to a voltage drop caused by the input current of the amplifier. It is important to notice that the precision of the resistor is not critical to the the regulation of the strip voltage. With a small penalty in dc accuracy, resistors with tolerances of up to ±20% can be used. The circuit in Fig. 2b requires two connections to the detector strip (the biasing resistor and the feedback resistor) which result in an increased stray capacitance and may pose some assembly obstacles. To avoid these problems, a circuit was developed that is connected between the bias resistor and the bias power supply.

The circuit that controls the strip voltage and reduces the strip potential differences to less than few mV is shown in Fig. 3. Operational amplifier A is used to sense the strip current and to generate compensating voltage v_c so that the voltage v_s is equal to the bias voltage v_b. The amplifier is powered by floating power supplies referenced to the bias voltage. Amplifier A has a dc gain G and input offset voltage v_{of}. The input leakage currents are i_- and i_+. The circuit uses amplifier A (error amplifier) to balance the resistive bridge which comprises R_b, r_b, R_1, and R_2. The branch that comprises R_1 and R_2 is the reference branch, while R_b and r_b form the sensing branch.

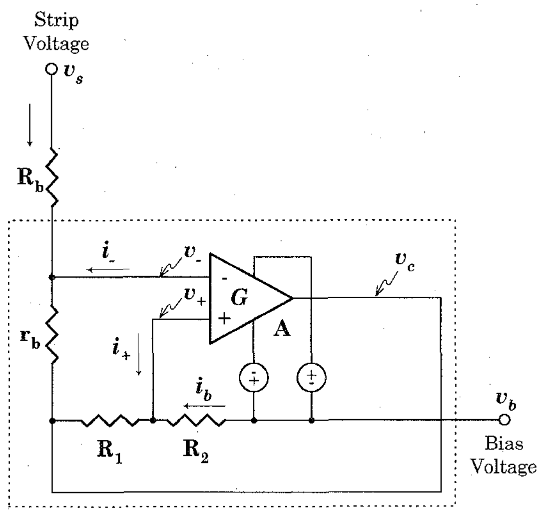


Fig. 3. Strip bias circuit using balanced resistor bridge.

The ratio between the resistors in the bridge branches must satisfy the following equation

$$\frac{R_b}{r_b} = \frac{R_2}{R_1} = \frac{1}{k}, \tag{1}$$

where k is a constant.

The dc analysis of the circuit leads to the following expression for the strip voltage v_s

$$v_s \cong v_b + \frac{(k+1)^2}{G \cdot k} R_b \cdot i_s + \frac{k+1}{k} v_{of} + i_+ \cdot R_2 - i_- \cdot R_b \cdot \tag{2}$$

Equation (2) shows that the effect of the strip current i_s is reduced significantly because k is usually between 0.1 and 1, and G is greater than 10^5. It is important for the ratios in the two branches to be well matched. If $\frac{R_b}{r_b} = \frac{1}{k}$ and $\frac{R_2}{R_1} = \frac{1}{k \cdot \Delta k}$ then the strip bias voltage v_s is given by

$$v_s \cong v_b + (1 - \frac{1}{\Delta k}) \cdot R_b \cdot i_s \cdot \qquad (3)$$

For simplicity the amplifier offset and input current error terms are neglected in (3). In order to reduce the dependence of v_s on i_s, Δk should be as close as possible to 1 (1 ±0.05).

The error amplifier output voltage (control voltage) v_c is

$$v_c \cong (k+1) \cdot R_b \cdot i_s \cdot \qquad (4)$$

The compensation voltage v_c may be used to measure the strip current. This measurement requires that the actual value of the resistors R_b and r_b be known. The strip current is given by

$$i_s = \frac{v_b - v_c}{R_b + r_b} \cdot \qquad (5)$$

For a given amplifier power supply, the constant k determines the range of the strip leakage currents i_S for which compensation can be achieved. Smaller values of k will result in a larger dynamic range of the controlled currents. Equation (2) shows that the errors associated with i_S and v_{of} increase when k decreases (k<1). Therefore, in order to maintain wide dynamic range of v_c and small error of v_s, it is necessary to select an error amplifier with both a high open loop gain and a small input offset voltage. In addition, the amplifier input currents should be less than a few pA.

A circuit was designed using LMC6062AI dual operational amplifiers [3]. Each of these amplifiers has supply current of only 25 μA and many of them can be powered by a floating battery power supply. These amplifiers exhibit extremely low input bias currents - 10fA to 100fA (4pA max) at room temperature. In addition, the input offset voltage is typically 100μV (350μV max at room temperature). The input offset current is half of the input bias current. The selection of R_2 becomes less critical since, in the worst case, the error due to the input currents of the amplifier will double relative to the case R_2=R_b. The open loop gain of LMC6062AI is typically 10^6 (10^5 worst case) and effectively reduces the effect of the $R_b i_s$ error term in (2).

The schematic of the strip bias voltage regulator is shown in Fig. 4. The most critical adjustment is to match the resistor ratio (constant k in (2)) in both bridge branches. This adjustment was done using the potentiometer *R3*. It is also possible to make this adjustment by using laser trimming of thick film resistors.

The potentiometer *R3* was adjusted using another amplifier LMC6062AI connected as a high impedance follower. The strip voltage node was connected to the input of the follower. The output was connected to a voltage meter, and two measurements were performed. First, the current flowing through R_b was set zero. In this case, the output voltage of the voltage follower represents the overall effect of all error terms in (2) plus some offset associated with the follower. Second, a 5 nA current is supplied to the strip voltage node. With this current flowing, *R3* is adjusted until the voltage at the output of the voltage follower became the same as the voltage measured with no current flowing.

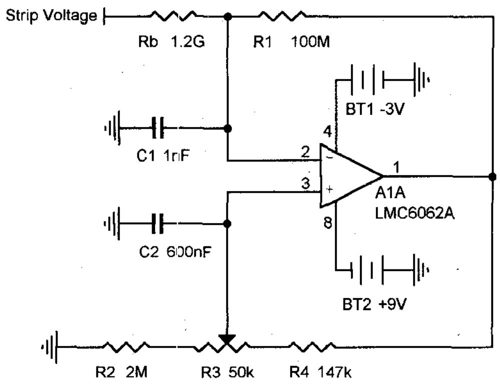


Fig. 4. Strip bias control circuit.

The capacitors *C1* and *C2* reduce the bandwidth of the circuit. The time constants of the two low pass filters in both bridge branches determine the stability of the circuit. For stable operation, the time constant of the reference branch should be equal to or greater than the time constant in the sensing branch. When both time constants are equal, the circuit has the fastest settling time. If the time constant of the sensing branch is larger than the time constant of the reference branch, the circuit is unstable.

A prototype circuit similar to the circuit in Fig. 2b was also built using the LM6062AI operational amplifier. This circuit does not need any adjustments and regulates the strip voltage to within few mV of the bias voltage. Measurements were made to evaluate the performance of both circuits and to study the behavior of a CZT strip detector under different bias conditions.

III. Tests with CZT Strip Detector

The bias voltage control circuits were applied to a prototype CZT strip detector [4] with strip leakage current of about 1nA. The standard bias scheme of this detector includes bias resistors of 1.2GΩ ±20%. We tested both circuits (Fig. 2b and Fig. 4). Fig. 5 shows the test configuration. The strip bias circuits were connected between ground and four contiguous anode strips marked as 15, 16, 17 and 18. A bias voltage of -200V was applied to the cathode strips. The strips adjacent to the test strips were grounded.

Each of the four anodes involved in the measurements had its own preamplifier, and the gains appeared well matched. In order to minimize systematic errors due to gain mismatches, the same shaping amplifier and discriminator assembly measured the counting rate for each strip. An

^{241}Am source provided a flood illumination on the anode side of the detector. By restricting photon interactions to the region just above the anodes, the short mean free path of the 60 keV photons (0.26 mm) in CZT helps to minimize the effects of material non-uniformity in the 1.5 mm thick detector. The strip pitch is 0.375 mm.

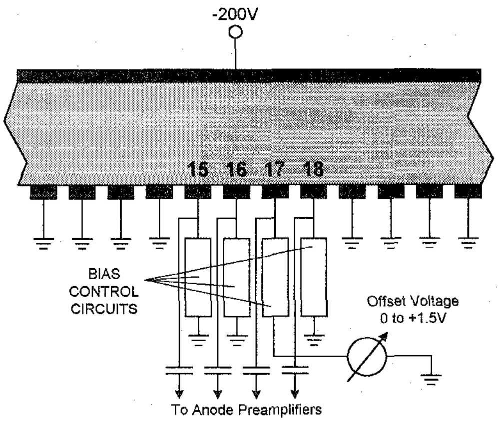


Fig.5. CZT strip detector test configuration.

With the bias equalizing circuits in place, we measured the counting rate for each anode. The measurements were then repeated with the strip bias circuits bypassed and all anodes connected to ground through 1.2 GΩ bias resistors. The bias resistors for strips 15, 16, 17, and 18 were the same as those used in the bias control circuits. We then calculated a normalized counting rate, defined as the ratio of an individual anode counting rate divided by the sum of all four anode counting rates, for each strip. Fig. 6 shows the normalized counting rates for the test strips. Note that when the strip bias circuits are used, the relative rate for each strip is about 0.25 (as would be expected in a flood illumination), but when the equalizing circuits are bypassed, the rates change significantly.

The bias resistors of the test strips 15, 16, 17, and 18 were measured to be $R15$=1.05GΩ, $R16$=1.08GΩ, $R17$=1.13GΩ, and $R18$=1.22GΩ. If the strip leakage currents are the same there should be correlation between the resistor values and the observed variations in the counting rates. From the data in Fig. 6 and the resistor values it is not obvious that such correlation exists.

The leakage currents for the test strips were measured with the bias control circuits in place. In this case the test strips are kept at the same potential. Therefore, the measured leakage currents exclude any possible surface current flowing between the strips. The control voltage v_c was measured, and using (5) the leakage current for each strip was calculated. The leakage currents for the four strips 15, 16, 17 and 18 were 0.85nA, 1.34nA, 1.08nA, and 1.55nA respectively. Measured leakage currents corresponded inversely to counting rates when the bias circuits were bypassed; strips with higher leakage currents had lower counting rates.

We further investigated the effect of differential bias voltage varying the potential at strip 17 from 0 to 1.5V. Fig. 7 shows the normalized counting rates when the voltage at anode 17 was increased while the other three anodes were kept at constant 0V by the bias control circuits. Note that a voltage change of only 0.1V (0.05% of the detector bias voltage) produces a noticeable effect. Similar results have been observed in a previous study of anode counting rates [2].

Fig. 8 shows leakage currents for this set of measurements. The leakage currents on anode strips 15 and 18 remain fairly constant, while those on strips 16 and 17 vary. It appears as though strip 17 is stealing current from strip 16 but not from strip 18. This effect requires further study.

The noise contributions of the circuit in Fig. 4 were also investigated. The RMS noise at the output of the shaping amplifier (1.5μs time constant) was first measured with 1.2GΩ bias resistor. When the circuit in Fig. 4 was substituted for the resistor no change of the output noise was observed.

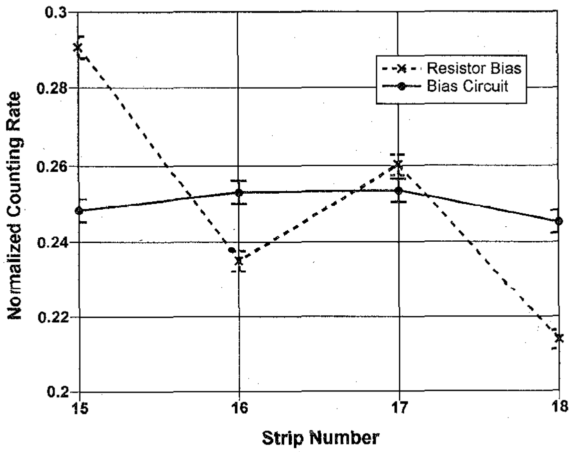


Fig. 6. Normalized counting rates for the test strips, with and without bias control circuits.

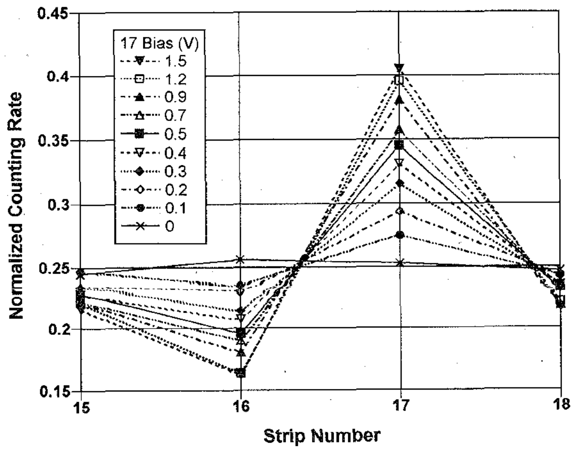


Fig. 7. Normalized counting rates at different bias voltages of strip 17.

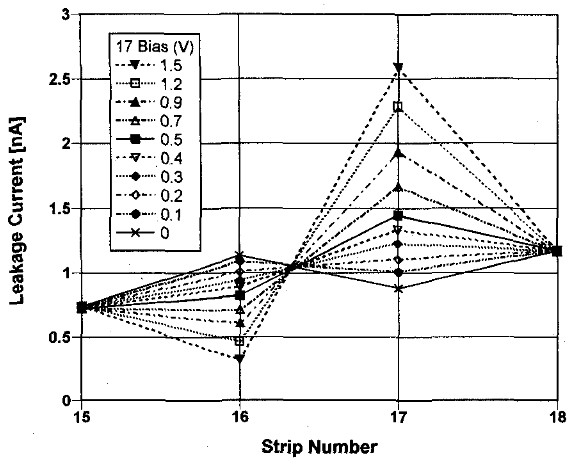


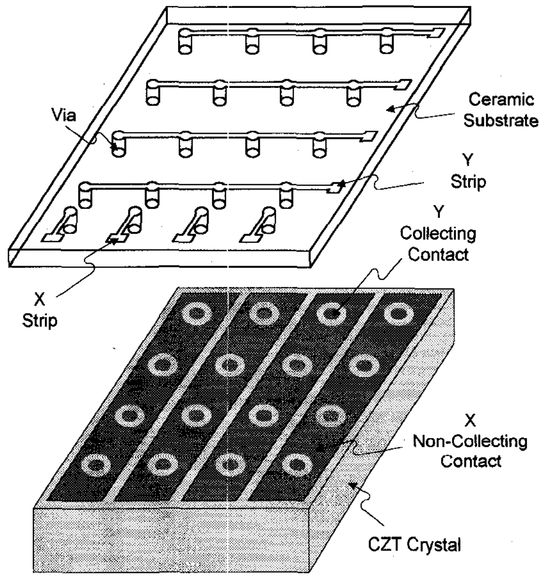
Fig. 8. Leakage currents at different bias voltages of strip 17.

IV. DISCUSSIONS

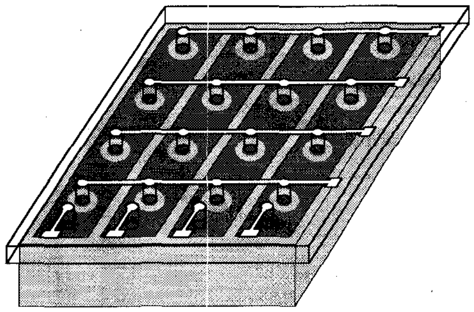
Two circuits were built and tested with a CZT strip detector. The circuits were capable of equalizing strip bias voltages and resulted in improved uniformity in a flood counting rate experiment. The circuits also allowed us to offset the bias voltage of one strip while the bias voltages of the others were kept constant. Significant changes in the strip leakage current and the strip counting rate were observed with only few hundred millivolts of differential strip bias voltage, a very small fraction of the 200V detector bias voltage. Therefore, the observed effects most likely are due to surface or near surface material properties of the detector in addition to significant changes in the electric fields near the surface.

While demonstrated here for anodes, the bias control circuit can be applied to the cathode strips or to electrodes at any potential. The bias control circuit may become important in the investigation of new types of imaging devices using room temperature detectors. Recently, a single carrier contact configuration was demonstrated that utilizes a control electrode and improves the spectroscopic performance of monolithic CZT detectors [5]. It is possible to build a single carrier "strip" detector based on a similar contact configuration. Fig. 9 shows the construction of such a detector.

The signal from the collecting anode contact provides the pulse height information and also indicates the position of the interaction in one dimension. The induced signal in the non-collecting electrode defines orthogonal position. The detector is biased by voltage applied to the cathode (bottom of the crystal in Fig. 9). The non-collecting or controlling electrode is biased relative to the collecting electrode. The potential difference between these electrodes can be on order of a few tens of volts. Therefore, the use of bias control circuits applicable at any potential will be helpful in the characterization and the development of such single carrier imaging detectors.



a)



b)

Fig. 9. Construction of single carrier strip detector.

V. REFERENCES

[1] J. L. Matteson et al., "CdZnTe arrays for astrophysics applications" *SPIE Proc.*, Vol. 3115, pp.160-175, 1997.

[2] M. Mayer et al., "Performance and Simulation of CdZnTe Strip Detectors as Sub-millimeter Resolution Imaging Gamma Radiation Spectrometers", *IEEE Trans. Nucl. Sci.* Vol. 44, pp 1458-1462, 1997.

[3] *Operational Amplifiers Databook*, National Semiconductor, 1995.

[4] J. R. Macri et al., "Development of an Orthogonal-Strip CdZnTe Gamma Radiation Imaging Spectrometer", *IEEE Trans. Nucl. Sci.*, Vol. 43, pp 1458-1462, 1996.

[5] J. F. Butler, "Novel electrode design for single-carrier charge collection in semiconductor nuclear radiation detectors", *Nucl. Instr and Meth.*, Vol. A 396, pp 427-430, 1997.