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데이터 획득장치에 이용되는 포토센서에 대한 DAS의 신호분석연구

A Study on Signal Analysis of the Data Aquisition System for Photosensor

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요 약

slip-ring 기술을 가진 spiral CT의 주요 장점으로는 X-ray 튜브의 연속적인 회전에 의해 환자에 대한 정보의 손실 없이 데이터를 연속적으로 획득할 수 있다는 것이다. 또한, X-선량의 인체 흡수의 감소를 위해서, 고시그널 저노이즈 및 빠른 데이터 획득 시간을 갖는 시스템이 요구되어 진다. 본 연구에서, CT 적용을 위해 다채널 포토센서 및 데이터 획득 시스템이 개발되어 졌다. 포토센서의 모듈은 16채널 CdWO4 크리스탈 및 실리콘 베이스의 포토다이오드가 사용되었다. 또한, 포토센서로 부터의 입력 신호에 대한 전기적인 증폭을 위해, 트랜스 임피던스 스위치 인테그레이터가 사용되었다. 스위치 인테그레이터는 CT 적용에 대해 적합한 시그널 밴드와 노이즈 퍼포먼스를 갖고 있다. 데이터 획득과 20 bit ADC 의 컨트롤은 FPGA를 이용하였고, 코딩은 VHDL을 사용하였다. CdWO4 기반의 실리콘 포토센서와 고SNR 및 좁은 시그널 밴드를 가진 증폭단 및 FPGA기반의 디지털 하드웨어는 CT적용 이외에 하드웨어 변경 없이 다른 분야에서도 이용 가능하다.

ABSTRACT

The major advantage of slip-ring technology in Spiral CT is that it facilitates continuous rotation of the x-ray tube, so that volume data can be acquired from a patient quickly. Not only for such a fast scan, but also for the dose reduction purpose, high signal-to-noise ratio and fast data acquisition system is required. In this study, we have built a multi-channel photodetector and multi-channel data acquisition system for CT application. The detector module consisted of CdWO4 crystal and Si photodiode in 16 channels. For the performance test of the preamplifier stage, both the transimpedance and switched integrator types are optimized for the photodetector modules. Switched integrator showed better noise performance in the limited bandwidth which is suitable for the current CT application. The control sequence for data acquisition and 20 bit ADC is designed with VHDL(Very High Speed Integrated Circuit Hardware Description Language) and implemented on FPGA(Field Programmable Gate Array) chip. Our Si photodiode detector module coupled to CdWO4 crystal showed comparable signal with other commercially available photodiode for CT. Switched integrator type showed higher SNR but narrower bandwidth compared to transimpedance preamplifier. Digital hardware is designed by FPGA, so that the control signal could be redesigned without hardware alteration.

Keyword : Signal Analysis, Photo detector, Switched integrator, ADC, SNR

1. INTRODUCTION

Compared to the conventional single slice or multi-slice X-ray CT, the spiral X-ray CT has advantage so fast s canning time and patient dose reduction. However, in order to achieve these, not only the detector but also the data

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acquisition system(DAS) should be fast and have the high signal-to-noise ratio. The DAS, positioned between the detector array and the computer, performs the following three major functions; (1) amplifying the signal from detectors, (2) converting the analog signal into the digital data, (3) transmitting the digital data to the computer for reconstruction and further image processing. The detector signal is generally very weak so it is preamplified before it is converted into digital data.

In this study, a 16-channel data acquisition system with bit resolution is developed. Also a 16 channel detector module consisted of 16 $CdWO_4$ crystal and photodiode array was prepared for the test of the developed DAS.

2. MATERIALS AND METHODS

2.1 CONFIGURATION OF THE SYSTEM

The developed system is made of a 16 channel detector, a 16 channel pre-amplifier, an A/D converter, a digital logic interface and a user interface as shown in Figure 1. common-mode rejection and impedance matching. ADC(ADS1250) was used to digitize the amplified analog signal.[3]

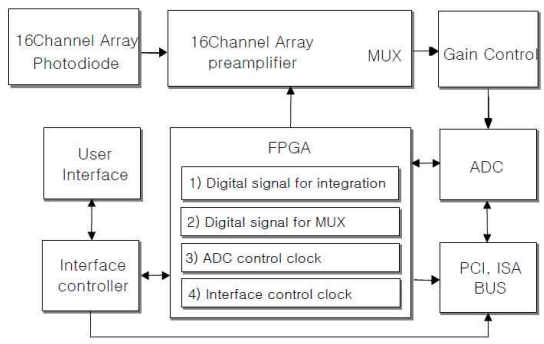

그림 1. 데이터 획득장치 블록다이어그램
Fig. 1 Block Diagram of Data Acquisition System

The detector module consists of 16 $CdWO_4$ crystal and photodiode array. Each element of the crystal array has a dimension of 1mm x 3mm x 20mm and it is polished and Teflon-taped for signal light reflection and anti-cross talking. Figure 2. shows the assembled detector array to the test jig with a 16 channel collimator.

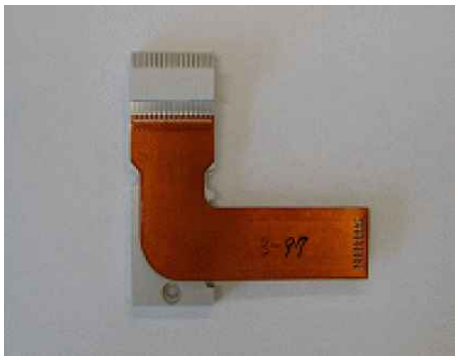

그림 2. 검출기 어레이 모듈
Fig.2. Detector array module

For the pre-amplifier stage, we have tested two configurations as in Fig.3, 1) transimpedance amplifier(OPA124) + dual integrator(OPA124) 2) switched dual integrator(ACF2101) as a preamplifier. A dual integrator(an odd integrator and an even integrator) is used in order to achieve the zero integration dead time for maximum utilization of detector signal during the continuous scan. While the detector signal charge is integrated in one integrator, the signal in the other integrators is transmitted into the ADC through a MUX. For the maximum signal-to-noise ratio, the impedance matching between the photodiode and the pre-amplifier is accomplished by feedback capacitor for transimpedance amplifier. The impedance can be matched without feedback resistance for switched integrator. The gain peaking, offset compensation, the bandwidth, noise and phase margin of preamplifier are considered in design. Since switched integrator pre-amplifier showed better performance in our application, this type of pre-amplifier is used for the rest of the experiment. [2]

The outputs of the 16 integrators(ACF2101) are multiplexed by the select switch to buffer (OPA2107) which prevents the signal crosstalk. Then the signal is delivered to a monolithic gain(=10) differential amplifier (INA106) to control the gain with a potentional-meter. A small resistance is added to both the inverting input and

the noninverting input to maintain good common-mode rejection and impedance matching. ADC (ADS1250) was used to digitize the amplified analog signal. [3]

Finally, the timing and the control signal for the integrators, the address signal of the M, the timing signal of PGA-ADC and the control signal of data transmission are generated in the digital logic board implemented by a FPGA which was coded with VHDL. [6,7]

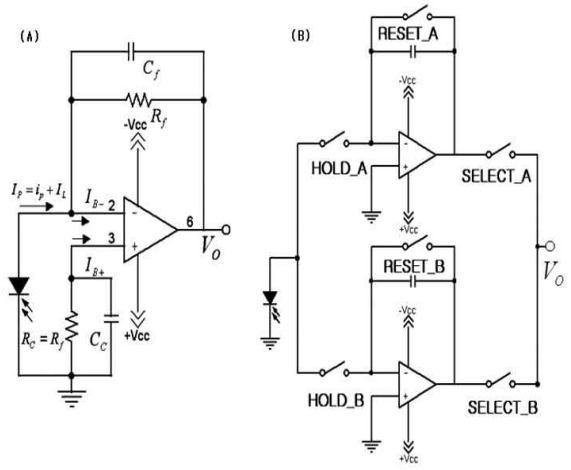

그림 3. (A) Feedback resistance를 이용한 트랜스임피던스 증폭기 (B) 스위치 듀얼 적분기 블록다이어그램

Fig. 3 (A) transimpedance amplifier using feedback resistance. (B) block diagram of switched dual integrator

2.2 NOISE ANALYSIS

The photodiodes have the junction capacitance of 35pF and the shunt resistance of 30MΩ at zero bias(photovoltaic mode). The reverse current at 5 V is around 1 nA. The photovoltaic mode of operation is preferred when a photodiode is used in low frequency application(up to 350kHz) and less sensitive to temperature.

Transimpedance amplifier, which is low-input current FET, is used to monitor photodetector. The noise gain response for the transimpedance amplifier is shown in Fig. 4. The feedback resistance and capacitance control the bandwidth and the noise of the amplifier, which should be optimize to closely match the physical system bandwidth.

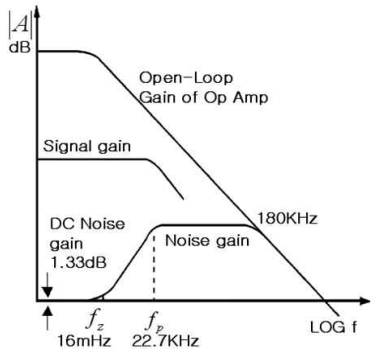

그림 4. 트랜스임피던스 증폭기의 노이즈 이득응답

Fig. 4 Noise gain response of transimpedance amplifier

The total noise of transimpedance amplifier can be computed by RMS(Root Mean Square) summation of the each noise components.

Thus the total noise is

$$E_{n\,total} = \sqrt{E_{noe1}{}^2 + E_{noe2}{}^2 + E_{noe3}{}^2 + E_{noR}{}^2 + E_{noi}{}^2} = 98\mu V_s \quad (1)$$

E_{noR}, E_{noi}, and E_{noe} represent the output noise component produced by the resistor itself, the amplifier's input current noise, and the amplifier's input voltage noise, respectively.

E_{noe1}, E_{noe2}, and E_{noe3} are input noise voltages defined by pole and zero frequency. [1-4]

Using the feedback capacitance value caculated for a 65 degree phase margin, the effective signal and noise bandwidth is following : [1-4]

$$BW_{SIGNAL} = \frac{1}{2\pi R_{feedback} C_{feedback}} = 22.7kHz \quad (2)$$

$$BW_{NOISE} = \frac{1}{2\pi R_{feedback} C_{feedback}} = 71kHz \quad (3)$$

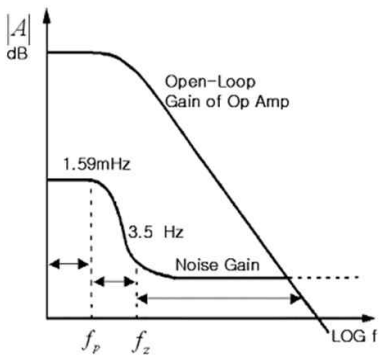

그림 5. 스위치 적분증폭기의 노이즈 이득응답

Fig. 5 Noise gain response of switched integrator amplifier

The noise gain response for the switched integrator during integration mode is shown in Fig. 5. The typical on-resistance of the hold switch is 1.5kΩ, and the typical open-resistance of the reset is 1000GΩ.

The low frequency pole of the noise gain is equal to :

$$f_p = \frac{1}{2\pi R_{RESET} C_{INT}} = 1.59mHz \quad (4)$$

where $R_{RESET} = 1000\text{G}\Omega$ and $C_{INT} = 100\text{pF}$ in our circuit. The pole frequency would occur at 1.59mHz. This pole is usually found at very low frequencies. The zero frequency of the noise gain plot is equal to :

$$f_z = \frac{1}{2\pi (R_1 \| R_{RESET})(C_1 + C_{INT})} = 3.5Hz \quad (5)$$

where R_1, shunt resistance, is 30MΩ, C_1, the junction capacitance, is 350pF. This zero frequency is also usually found at low frequencies. In our circuit, f_z is 3.5Hz. [1-4]

Since the noise spectrum shows high only in the very low and narrow, e.g. below 3.5Hz, the total noise is largely determined by the bandwidth and noise density of the high frequency region. [1-4]

$$\text{High frequency noise gain} = \left(1 + \frac{C_1}{C_{INT}}\right) \quad (6)$$

The total rms noise is estimated as equal to

$$\text{Total rms noise} = \left(1 + \frac{C_1}{C_{INT}}\right) = 45\mu V_s \quad (7)$$

3. RESULTS

3.1 Detector module

Our photodiode is made of 280㎛ thick, 2600 Ω·cm resistivity, n-type substrate wafer. Its p-layer, i-layer(v-type), n^{++}-layer is 3, 77, 200㎛ thick, respectively. The measured junction capacitance was 5pF. However, other commercial module junction capacitance were 350-400pF.

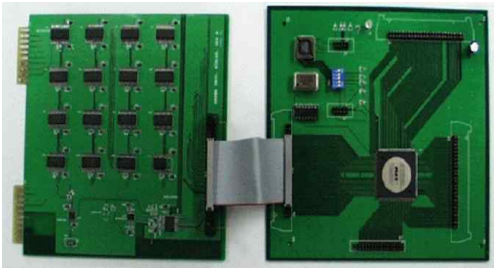

그림 6. 아날로그 및 데이터획득 보드
Fig. 6 Analog and Digital Data Acquisition Board

Under the tube voltage 100kVp, tube current 20mA, and X-ray pulse time 8.3ms, the signal magnitude was 40nA for our photodiode, and 80nA for the commercial ones. If its signal is normalized to its area, the normalized signal is comparable.

3.2 The pre-amplifier - Transimpedance and Switched Integrator Type

The performance of transimpedance and switched integrator was compared under the tube voltage 100kVp, tube current 20mA, X-ray pulse time 8.3ms.

Table-I is summery of measured value of junction capacitance and dark current of photodiode and calculation result while the signal current of photodiode maintains 30nA at zero bias condition, integration time is 1ms, discharge time is 50ms. The GBP calculation for the transimpedance amplifier used phase margin. [1]

표 1. 트랜스임피던스 증폭기와 스위치 적분기의 노이즈, 대역폭 성능의 비교
Table 1. Comparision of noise and bandwidth performance between a transimpedance amplifier and a switched integrator

	Transimpedance Amplifier	Switched Integrator
Junction Capacitance of Photodiode	350p	350p
Dark Current	1nA	1nA
Input Bias Current	1pA	1pA
Total Gain	10^7	10^7
Signal Bandwidth	22KHz	10KHz
Noise Bandwidth	71KHz	250KHz
Total Noise	98μVrms	45μVrms

3.3 Data Acquisition System

For the performance test of the switched integrated type DAS, green LED, which has similar wavelength of scintillating light of $CdWO_4$, was used as light source instead of X-ray. The DAS gain was set to 10^8, which is in series connection of 10^7 gain in switched integrator and 10^1 gain in the gain controller(INA106). Total noise of the DAS is measured atthe output of the ADC with 25kHz bandwidth under constant irradiation of green LED. Forthe ADC noise measurement, variance value was measured under constant DC voltage applied as ADC input signal. The dynamic range is defined as a reciprocal of standard deviation in ppm.

표 2. 스위치 적분기, 이득제어기, 멀티플렉서와 아날로그디지털변환기를 통한 Total 노이즈

Table 2. Total noise through a switched integrator, gain controller, multiplexer and ADC.

Optimum Performance	
Total Gain	10^8
Standard Deviation under constant irradiation	50ppm
Standard Deviation of ADC value under constant DC signal	4.3ppm
Total Noise	200μVrms
Dynamic Range	86dB

4. DISCUSSION

X-ray irradiation experiment showed the Si photodiode comparable signal to other commercial photodiode, yet to be improved. There could be several ways for the improvement. One is to reduce p-layer thickness, since much of light emitted from scintillator is absorbed in p-layer. In this study, photodiode with 3mm thick p-layer is used. Later version is reduced down to 1.8 or less than 1mm by ion implantation process.

This method still could be susceptible to surface contamination. The other is to form a junction underneath the surface by ion implantation, so that less susceptible to the surface contamination. This method also will provide very thin surface layer down to under 1 mm, so that transparent to more light photons.

Since the noise characteristics in a photodiode-preamplifier unit is related to many physical and electric parameters of the photodiode and the preamplifier, it needed to be optimized. By proper choice of feedback capacitor maximize SNR. We compared the detector-preamplifier system between transimpedance amplifier and switched integrator for various parameters. It is important to make proper selection of the component value of circuit through phase analysis and impedance matching. The feedback capacitor used for the transimpedance type was 0.7pF considering 65degree phase margin for stability and increased GBP.

In switched integrator type, a large feedback capacitor, 100pF, is used to improve the noise performance of the circuit. The noise performance of the switched integrator is improved over the transimpedance amplifier, yet the bandwidth is considerably smaller. ADC noise is 4.3ppm which is corresponding to 108dB. This is quite close to ideal dynamic range 120dB. Also, the readout circuit for the DAS should have a uniform frequency response in the wide dynamic range.

5. CONCLUSION

The scintillator-photodiode detector module was developed, yet to be improved. The switched integrator preamplifier type showed better SNR performance in limited frequency bandwidth. Second stage and ADC noise was negligible for the amplified signal. Efficient, flexible and compact design of hardware was possible using FPGA. All the experiment was done with prototype made on breadboard, so that more noise was observed than we expected. We are observing less noise with in digital signal as well as analog signal along the progress we make the electronics in multi-layer PCB. We expect much improved SNR in detector module and DAS with a few improvement.

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