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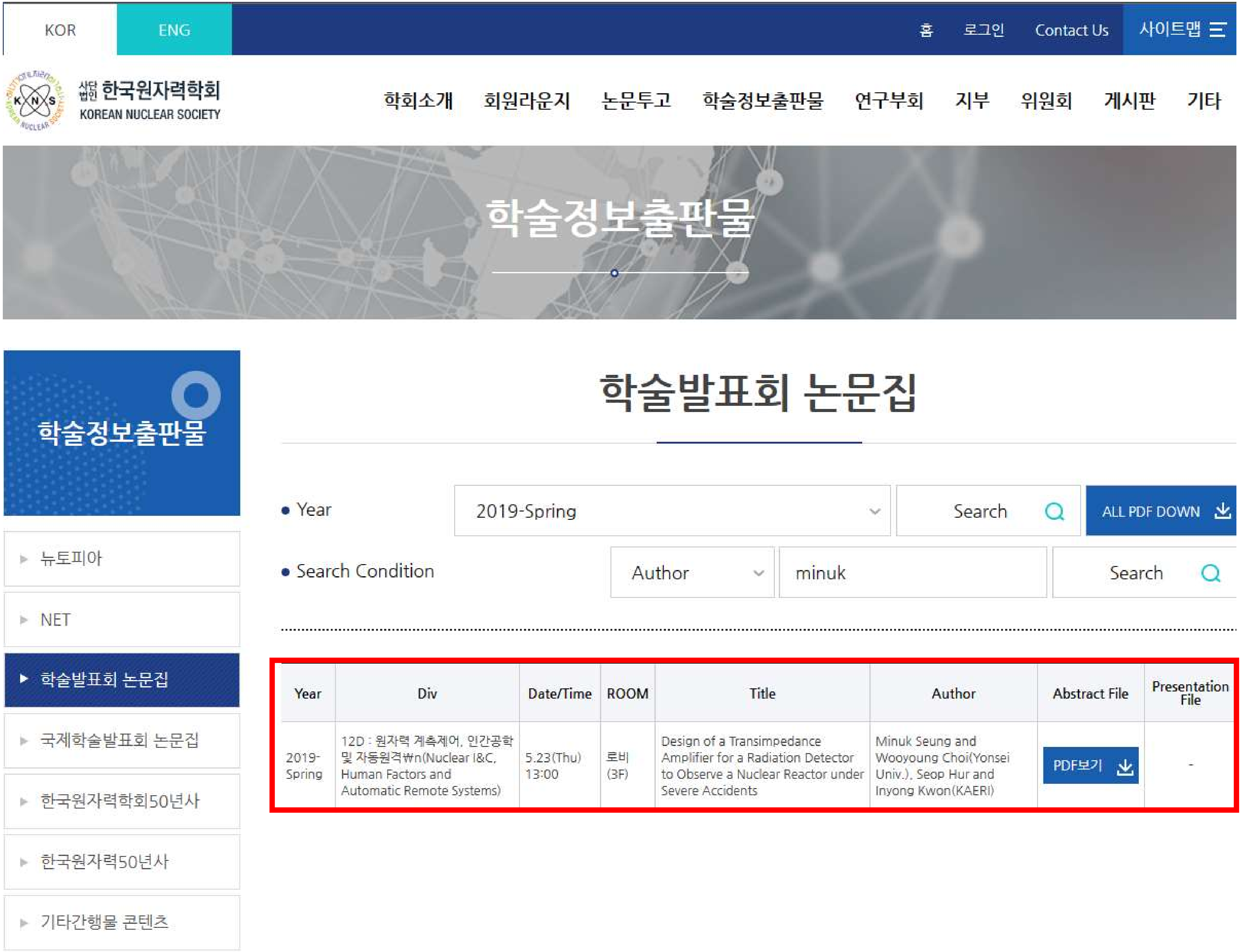

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Design of a Transimpedance Amplifier for a Radiation Detector to Observe a Nuclear Reactor under Severe Accidents

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1. Introduction

The issue of the safety of the nuclear power plants (NPPs) has been continued after the Fukushima nuclear accident. It is difficult to observe the reactor's internal situation directly, when a serious accident occurs. Instead, it is possible to predict the inside situation of the reactor by measuring temperature and radiation indirectly.

The coolant level can be accurately predicted, if we can measure the radiation in the linear direction using collimators to reduce nonlinear direction radiation effect, because the radiation dose varies by the level of the coolant inside the reactor along with shielding materials.

In Fig.1, red lines are nonlinear radiation coming out of the reactor that is shielded by collimators and blue lines are linear radiation and which can be measured by detector.

In addition to the radiation measurement, we can predict the situation inside the reactor sufficiently, if the outer temperature of the reactor can be measured at the same time.

The conventional preamplifier used in a radiation detector consists of charge sensitive amplifier (CSA) and shaping amplifier (SA) [1]. This preamplifier has a delay time of several microseconds because of the charge integration time. Instead, a transimpedance amplifier (TIA) can convert from current to voltage directly and it can reduce delay time [2].

The basic TIA circuit is shown in Fig.2. The OP-AMP has comparatively high impedance. So all of the input currents ideally flow into the feedback resistor. Therefore, Ohm's law governs the output voltage [3]. It certifies that the feedback resistor contributes the TIA gain apart from the open loop gain of OP-AMP [4, 7].

$$V_{out} = I_{in} \times (-R_f) \quad (1)$$

This paper will introduce a TIA design that can be read-out high activity radiation signals, and will show simulation results with a conventional transistor model.

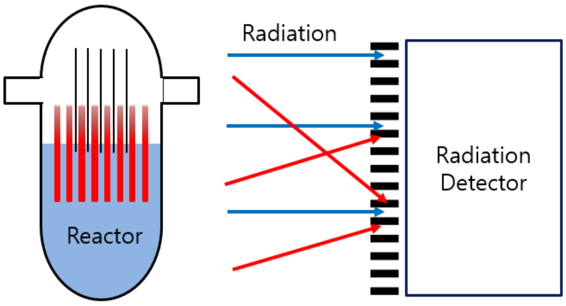


Fig. 1. Concept of the radiation detection method when occur the severe accident.

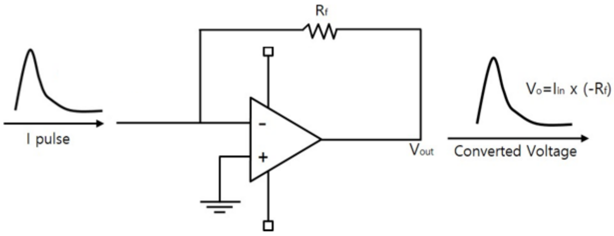


Fig. 2. A basic transimpedance amplifier topology.

2. TIA design

2.1 Operational amplifier for TIA

The basic TIA circuit consists of OP-AMP and feedback components. The dominant pole of the system is determined by time constant $R_F C_{tot}$ and the gain bandwidth (GBW) of the OP-AMP [4, 5, 7]. So the Op-AMP was considered first.

$$f_c = \sqrt{\frac{GBW}{2\pi R_F C_{tot}}}, \quad (2)$$

where f_c is the overall system bandwidth of about 19 MHz, R_F is the feedback resistor of 80 $k\Omega$, and C_{tot} is the total capacitor of about 1.5 pF. C_{tot} is the capacitor which is the total input capacitance consisting of the photomultiplier tube(PMT) capacitance plus the OP-AMP input capacitance. The OP-AMP is designed with a single-ended two-stage amplifier structure in Fig. 3. The first stage converts differential signal to single-ended signal using a current mirror. The second stage amplifies the first stage output voltage. The Miller capacitor (C_C) is set to 500 fF for stable phase margin [6].

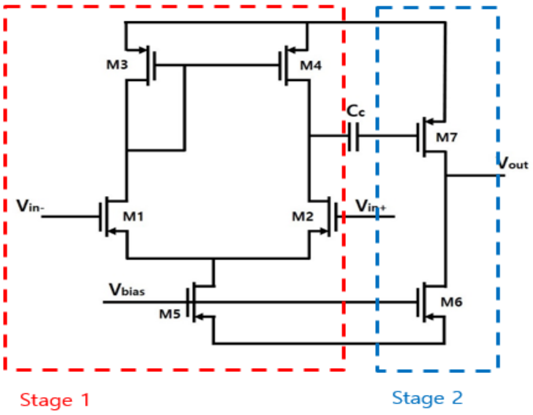


Fig. 3. The Two-Stage operational amplifier structure.

Table 1: The OP-AMP specifications.

Design Specifications	Value (Targeted)	Value (Obtained)
Supply (V_{dd})	3.3V	3.3V
DC gain	> = 70 dB	72.5 dB
BW(UGBW)	110 MHz	149 MHz
BW(3dB)	35 kHz	35 kHz
Phase Margin	60 deg	63.5 deg
Slew Rate(SR)	> = 150 V/µs	160 V/µs
CMRR	> = 60 dB	62 dB

Table 2: The OP-AMP design parameter.

Transistor	Width (µm)	Length (nm)
M1	6	350
M2	6	350
M3	12	300
M4	12	300
M5	0.45	350
M6	0.82	350
M7	42	300

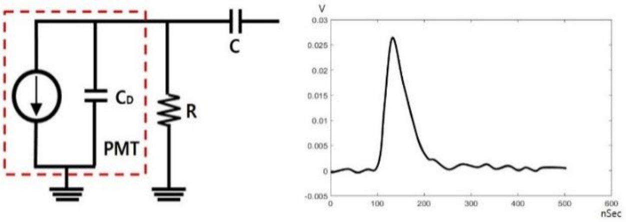
Table 1 shows the OP-AMP specifications for the designed TIA and Table 2 shows the design parameters. Generally, PMOS has lower mobility than NMOS [6]. Therefore, the width of PMOS is generally two times bigger than NMOS at the first stage.

2.2 Input current modeling

PMT used in this paper is R3991A-07 manufactured by HAMAMATSU. From the circuit model of the PMT in Fig. 4 (a), when the C is 4.7 nF and R is 110 kΩ for the Cs-137 radiation source, the output pulse height was 26.5 mV and pulse width is 100 ns. Based on these values, we could calculate output current of the PMT. Table 3 shows the input current properties.

2.3 TIA circuit design

The feedback resistor is set to 80 kΩ (98 dB) considering the input signal of the PMT.



(a) (b)

Fig. 4. (a) The PMT modeling with the coupling capacitor and (b) the output pulse waveform.

Table 3: The input current properties.

Properties	Value
Pulse width	33 ns
Pulse height	250 nA
Rise time	1 ps
Fall time	1 ps

The current will be expected to be converted to about 20 mV. The feedback capacitor is used for the stability of the TIA because the parasitic capacitor of the PMT could make the TIA unstable [3]. Therefore, the feedback capacitor C_f can be calculated as 140 fF by Eq. 3 [2] for system stability. Practically, however, C_f is slightly increased to 200 fF considering more phase margin (PM) of the system even though it occurs the 3-dB BW degradation.

$$C_f = \sqrt{\frac{C_{tot}}{2\pi R_f GBW}} \quad (3)$$

3. Simulation condition and result

3.1 Simulation condition

Fig. 5 shows the TIA topology designed by a standard 0.18 µm CMOS process for simulations. The IPULSE is the PMT equivalent circuit and it was set by the previously obtained current properties. A 4.7 nF capacitor and a 110 kΩ resistor were connected to maintain the waveform of the actual input signal.

3.2 Simulation results

The frequency response of the TIA circuit was measured as shown in Fig. 6. The 3-dB BW (about 14 MHz) is about four hundred times wider than the 3-dB BW (35 kHz) of the OP-AMP. Moreover, the TIA gain is about 98 dB. It means that all of the input currents flowed through the feedback resistor and that is independent of the gain of the OP-AMP.

Fig. 7 shows the input referred current noise. The input referred current noise is about 1.6 pA/$\sqrt{Hz}$ at the 3-dB frequency. It starts to rise slightly from about 0.1 GHz first, second much rapidly 1 THz.

Fig. 8 is the output waveform of the test circuit compared the input signal when period is 100 ns. The blue line is the input current pulse and the red line is the output current. The maximum output voltage is 1.669 V

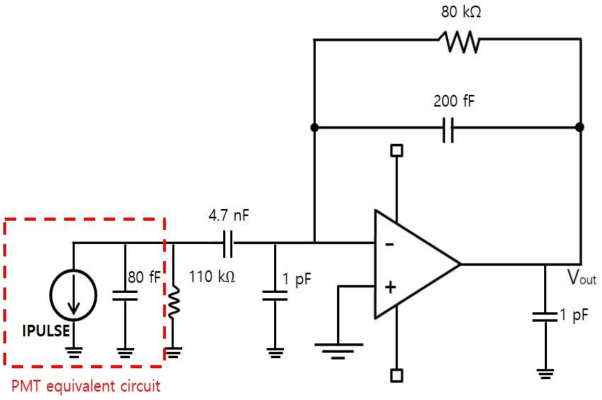


Fig. 5. The TIA topology.

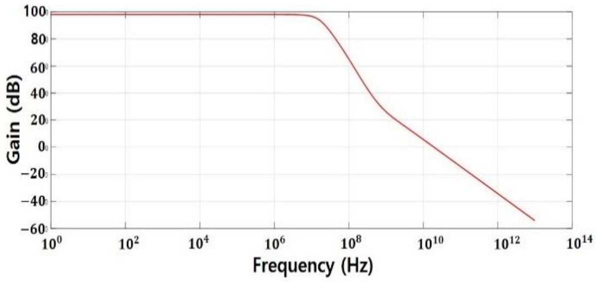


Fig. 6. The TIA frequency response of TIA simulation curve.

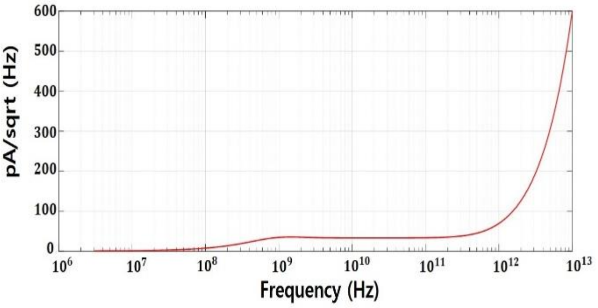


Fig. 7. The input-referred current noise of TIA simulation curve.

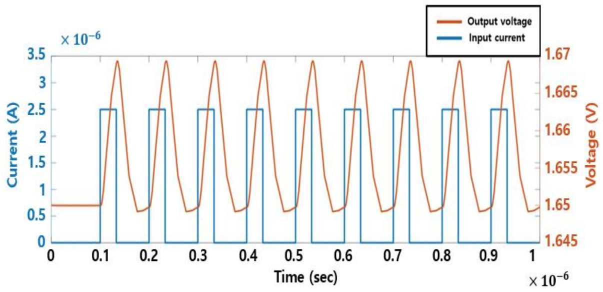


Fig. 8. The input signal of PMT and output signal of TIA simulation curve.

4. Conclusions

A TIA structure is widely used in the many fields, for example, optical devices, radiation detector, and current converter. In this paper, a TIA for radiation detector was designed and simulated. It shows that the TIA using OP-AMP can replace a CSA for radiation detector if it is sufficiently fast and stable.

Acknowledgements

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