CURRENT MODE TRANSIMPEDANCE AMPLIFIER FOR BEAM CURRENT MEASUREMENT

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Abstract

A two-stage current mode transimpedance amplifier, which uses two second-generation current conveyors, has been designed to measure beam current of the cyclotron at Korea Institute of Radiological and Medical Sciences(KIRAMS). It has a gain of 10^5 V/A, a bandwidth of 15.4 KHz, and an input dynamic range of 0.1 to 100 μA. The measured output noise voltage at 300^oK is less than 4 $\mu V/Hz^{1/2}$. When this amplifier and a beam probe were installed on a cyclotron to measure the beam current, the output waveform of the amplifier was suitable for monitoring the status of operation of the cyclotron.

INTRODUCTION

A 13 MeV cyclotron for positron emission tomography has been developed by the KIRAMS. This cyclotron uses a 77.3 MHz RF power to accelerate the beam. To monitor the status of operation of the cyclotron, an accurate measurement of the beam current is required. Typically, the beam current probe for a cyclotron picks up the charged particles using a conducting bar and a transimpedance amplifier is preferred to the other type of amplifier. The majority of the transimpedance amplifier has been built using a voltage mode operational amplifier with a feedback resistor. Because the gain-bandwidth product of a typical operational amplifier is constant, the achievable gain for a given voltage mode amplifier decreases when the bandwidth increases.

The second-generation current conveyor (CCII), which was introduced first by Smith and Sedra [1] and the small signal equivalent circuit for the CCII is shown in Fig. 1, is a three-port network whose voltage and current characteristics are given by the following equation:

$$\begin{bmatrix} i_Y \\ v_X \\ i_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_Y \\ i_X \\ v_Z \end{bmatrix}$$

where the ports X and Y are the input ports, the port Z is the output port, and the + and – sign of the current transfer ratio denote CCII+ and CCII-, respectively. It has been used in various circuits for analog signal processing, such as an instrumentation amplifier requiring a high common mode rejection ratio [2] or a wide bandwidth [3]. If we use CCII to implement a transimpedance amplifier, no feedback resistor is required because the magnitude of the output current i_Z is the same as that of the input current i_X. In this case, the bandwidth of the transimpedance amplifier is solely determined from the frequency characteristics of CCII itself, independent of the transimpedance gain, and the amplifier can operate at a much higher frequency than the one using a voltage mode operational amplifier.

In this paper, we propose a current mode transimpedance amplifier (CTA), which is implemented using a commercial current conveyor IC AD844 from Analog Device. This CTA uses two CCIIs and can measure the beam current as low as 0.1 μA. The design details of CTA are given in Section 2. The experimental results of CTA on the cyclotron at KIRAMS are given in Section 3, and a conclusion is given in Section 4.

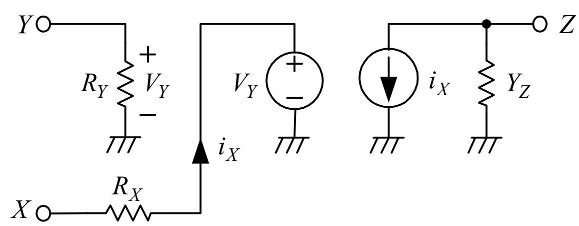

Figure 1: Small signal equivalent circuit for the CCII.

CURRENT MODE TRANSIMPEDANCE AMPLIFIER

The second-generation current conveyor AD844 from Analog Device has a high input resistance at the non-inverting input node (Y) and a low input resistance at the inverting node (X). The input resistance of the X node is 50 Ω. This device has two output nodes: the Z and TZ nodes. On this device, the input voltage of Y is transferred to X. The current into X is mirrored to the TZ node with unity gain. When a load is connected between TZ and ground, the developed voltage of TZ is buffered to Z with some voltage offset.

A CTA is implemented using two AD844s as shown in Fig. 2. In this circuit, the resistances of R_1, R_2, R_3, R_4, R_5, and R_6 are 2.25Ω, 30KΩ, 10KΩ, 250Ω, 1KΩ, and 1KΩ, respectively, and the capacitance of C_1 is 330 pF. The capacitor C_1 bypasses the high frequency noise and improves the signal-to-noise ratio of CTA. The output voltage V_{out} of this two stage CTA is given by the following equation:

$$V_{out} = \lambda_1 \lambda_2 \frac{R_2 R_5}{(R_x + R_4)(1 + sC_1 R_2)} I_{in} \quad (1)$$

where λ_1 and λ_2 are the current transfer ratios from X to TZ nodes of the first and second AD844s, respectively, and R_x is the input resistance of the X node. For

$\lambda_1 = \lambda_2 \cong 1$ and $R_x = 50\Omega$, the DC transimpedance gain of the circuit is $A_{ti} \equiv V_{out} / I_{in} = 10^5$ approximately.

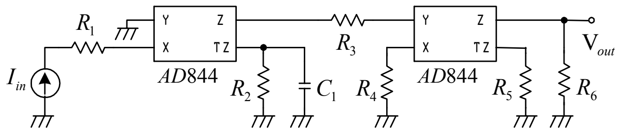

Figure 2: A two stages current mode transimpedance amplifier.

The frequency response of the two-stage CTA is analyzed using the equivalent circuit for the first stage, which is shown in Fig. 3. The second stage must have higher bandwidth because it is not connected an external capacitor such as C_1. The trans-resistance R_t and trans-capacitance C_c of the TZ port of AD844 are 3MΩ and 4.5pF, respectively [4]. Because $R_2 << R_t$ and $C_c << C_1$, the AC transimpedance gain of the first stage is given by the following equation:

$$\frac{V_o}{i_e} \cong \left(\frac{R_2}{1 + j\omega R_2 C_1} \right) \quad (2)$$

Therefore, the cutoff frequency f_c of the first stage is $1/2\pi R_2 C_1 \cong 16$ KHz. The measured cutoff frequency is 15.4KHz, justifying the equivalent circuit for AD844. This result shows that the $R_2 C_1$ time constant of the low-pass filter, which loads the TZ node of the first stage, limits the bandwidth of the proposed CTA. The cutoff frequency increases to ~ 1.18 MHz when C_1 is removed.

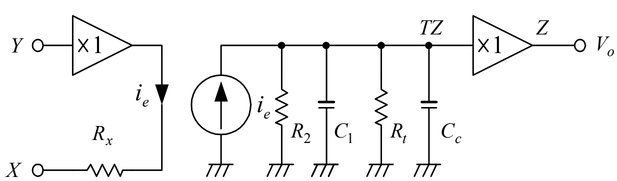

Figure 3: An equivalent circuit for the first stage of the two-stage CTA shown in Fig. 2.

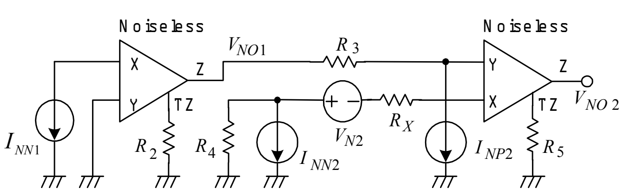

Figure 4: Noise model for the two-stage CTA.

A simple noise model for the two-stage CTA is given in Fig. 4. On the model, the current sources I_{NN1} and I_{NN2} represent the inverting input current noises of the first and second stages, respectively, and I_{NP2} represent the non-inverting input current noise of the second stage. The voltage source V_{N2} represents the amplifier internal input voltage noise of the second stage. The values of these noise sources for AD844 are $I_{NN1} = I_{NN2} = 10$ pA, $I_{NP2} = 12$ pA, and $V_{N2} = 2$ nV [4]. For this noise model, the noise voltages at the output nodes of the first and second stages are given by the following equations:

$$V_{NO1} = \sqrt{\left(I_{NN1} \times R_2\right)^2 + 4kTR_2}$$

$$V_{NO2} = \sqrt{\left(\frac{V_{NO1}^2 + \left(I_{NP2} \times R_3\right)^2 + V_{N2}^2 + 4kT(R_3 + R_4)}{\left(R_4 + R_X\right)^2} + I_{NN2}^2 \right) \times R_5^2 + 4kTR_5}$$

where k is the Boltzmann's constant and T is temperature in °K. At a temperature of 300°K, the calculated noise output voltage V_{NO1} at the first stage is about 300 nV/Hz$^{1/2}$ and V_{NO2} at the second stage is about 1 μV/Hz$^{1/2}$. From these results, it can be identified that the current noise at the input nodes of AD844 is the major noise source of the proposed two-stage CTA.

EXPERIMENTAL RESULTS

The measured output voltage versus input current of AD844AN is shown in Fig. 5. For this measurement, the nodes Y, Z, and TZ were grounded, open-circuited, and terminated with a load resistor of 99.98 KΩ, respectively. The input current was applied to X using a KETHLEY 220 current source, and the output voltages at Z and TZ were measured using a HP3458A digital voltmeter. Although AD844AN has a typical input bias current of 200 nA for the inverting node X, the measured results show that the transimpedance gain is fairly constant down to input current of 0.1 μA. Such a good characteristic is hardly achieved with the power supply current sensing method using an operational amplifier [5].

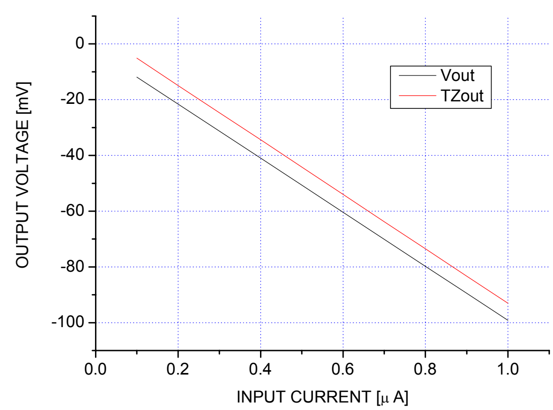

Figure 5: Measured output voltage versus input current of AD844.

To measure the transimpedance gain of the two-stage CTA, an input current of 10μA was fed into the circuit using a KETHLEY 220 current source and the output voltage was observed. The measured output voltage is 1 V, as shown in Fig. 6, which results in a transimpedance gain of ~ 10^5. This result agrees with the calculated transimpedance gain of 10^5 using (1). The measured output noise voltage spectrum at $I_{IN} = 1\mu$A is shown in Fig. 7. This noise spectrum was measured using a dynamic analyzer 35670A from Agilent Co. The measured maximum noise voltage is ~ 4 μV/Hz$^{1/2}$ which is slightly higher than the calculated noise voltage of 1 μV/Hz$^{1/2}$.

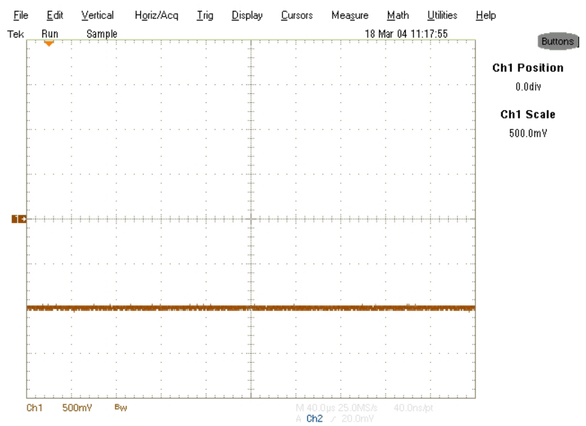

Figure 6: The measured output voltage of the two-stage CTA for an input current of 10 μA.

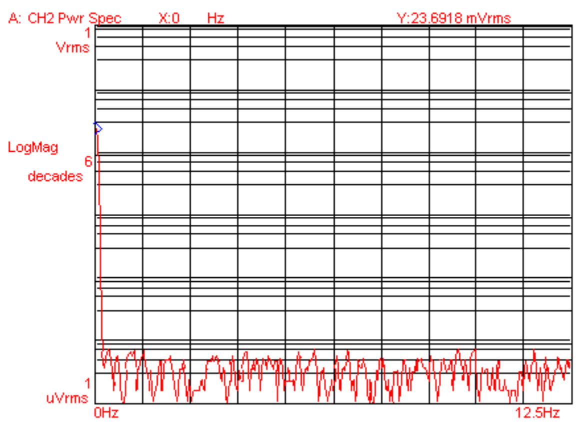

Figure 7: Measured noise spectrum of the two-stage CTA.

The beam current of the cyclotron at KIRAMS was measured using the two-stage CTA. The cyclotron was operated with a 77.3 MHz RF power to accelerate the beam. A beam probe was installed in the vacuum chamber of the cyclotron, and the current output of the beam probe was converted into a voltage output in the two-stage CTA. The observed current output waveform is shown in Fig. 8. This waveform takes a pulse shape, because the RF power was modulated by pulse width for the experiments, and has many spiky noises induced from the external noises sources such as the plasma power supply for an ion source, stepping motor drivers, etc. When we smooth out the waveform, the zero-to-peak output voltage is ~ 1.3 V, which corresponds a beam current of 13 μA.

Figure 8: Measured current waveform, which was modulated with the pulse width for system experiments.

CONCLUSION

A two-stage current mode transimpedance amplifier, which uses two AD844s second-generation current conveyor, has been designed to measure beam current of the cyclotron at KIRAMS. It has a transimpedance gain of 10^5 V/A, bandwidth of 15.4 KHz, and input dynamic range of 0.1 ~ 100 μA. The measured output noise voltage at 300^oK is less than 4 $\mu V/Hz^{1/2}$. Although many spiky noises due to external noise sources were observed when the circuit and a beam probe were installed on the cyclotron to measure the beam current, the two-stage CTA was very useful to monitor the status of operation of the cyclotron.

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