Development of the Low Noise Front-end Electronics for Pulse Voltage Stability Measurement

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***Abstract*—To meet the needs of pulse voltage flat-top stability measurement, this paper designs a high-precision, ultra-low-noise front-end electronics “SAFee”. The key part of “SAFee” consists of a discrete three-op amp instrumentation amplifier. The two inputs are the high-precision reference voltage provided on the board and the external input pulse. By taking the difference between two inputs, the pulse flat top is adjusted to “near 0V”, and then use an oscilloscope to measure its stability. The “SAFee” board can provide -10 V~10 V DC bias adjustment capability. The measured output RMS noise is $150.34 \pm 1.13\ \mu V$, which can achieve 50 ppm accuracy measurement of the target solid-state pulse modulator.**

***Index Terms*—Low noise, instrumentation amplifier, front-end electronics, pulse voltage stability.**

I. INTRODUCTION

THE high-voltage solid-state pulse modulator is used to drive high-power microwave klystrons. The pulse-to-pulse flat-top stability of the high-voltage pulse modulator will directly affect the consistency of the accelerated electron beam energy. Under normal circumstances, the high-voltage pulse output by a solid-state pulse modulator can reach hundreds of kilovolts, and the pulse-to-pulse stability needs to reach 50 ppm to 10 ppm, or even lower. Under a 10 V pulse voltage, 10 ppm stability will correspond to 10 µV RMS noise. This requirement for the noise floor of the measurement equipment makes it impossible for ordinary data acquisition systems or oscilloscopes to complete the measurement well.

In order to achieve the stability measurement of 10V high-voltage pulses on an oscilloscope, this paper designs a low-noise front-end electronics to adjust the high-voltage pulse bias to near 0 V, and then uses the oscilloscope to perform measurements at a resolution of 1 mV/div.

II. DESIGN OF LOW NOISE FRONT-END ELECTRONICS

The front-end electronics studied in this paper will receive high-voltage pulses after capacitor voltage division. At this time, the pulse top is about 10 V. Therefore, the front-end electronics needs to provide a clean 10 V DC voltage to make a difference with the input 10 V voltage pulse, thereby shifting the flat top of the pulse of interest to near 0 V.

The front-end electronics studied in this paper is based on a discrete three-op-amp instrumentation amplifier, which can be divided into three parts: input buffer stage, used for impedance matching; differential stage, used to make a difference between the input voltage pulse and DC voltage; output stage, pulse flat-top amplification, for oscilloscope measurements. The classic three op-amp in-amp was chosen in this study, and the system circuit is shown in Fig. 1.

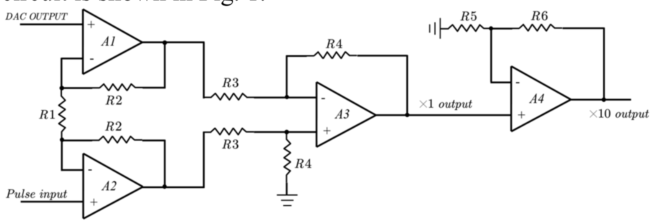

Fig. 1. The low noise front-end electronics schematic based on discrete three op-amp instrumentation amplifier.

Table I shows some important specifications of the modulator to be tested. Therefore, the performance requirements for the front-end electronics part can be estimated as follows, can provide high-precision ultra-low noise DC bias voltage between -10 V-10 V, bandwidth greater than 10 MHz, the overall noise contribution of the measurement system is less than 159.33 µV RMS and the slew rate is greater than 29.92 V/µs.

TABLE I
MODULATOR SPECIFICATION

Description	Result
Output Voltage	-160 kV
Output Current	116 A
Voltage Rise Time (10%-90%)	≤1 µs
Voltage Fall Time (90%-10%)	≤1 µs
Pulse Half Width	5.5 µs
Flat Top Ripple or Droop	≤±1%
Voltage Pulse to Pulse Stability	≤50 ppm (rms)
Pulse Leading Edge Jitter	≤10 ns (rms)
Repetition Rate	≤250 Hz

III. CIRCUIT ANALYSIS

The common mode rejection ratio (CMRR) of the discrete instrumentation amplifier shown in Fig. 1 can be expressed as Equation (1),

$$\mathrm{CMRR} = \frac{G \times CMRR_3 \times CMRR_{12}}{G \times CMRR_3 + CMRR_{12}} \tag{1}$$

Manuscript received May 19th, 2024.
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where the G is the gain of the first stage, CMRR_{12} is the CMRR of first stage, it can be expressed by Equation (2). Where the CMRR_1 and CMRR_2 is the CMRR of amplifier A1 and A2, respectively.

$$\mathrm{CMRR}_{12} = \frac{CMRR_1 \times CMRR_2}{CMRR_1 - CMRR_2} \tag{2}$$

Therefore, the parametric matching of the first-stage op amp, higher first-stage gain, higher second-stage op amp CMRR, and second-stage precision matching resistor network with higher CMRR will improve the CMRR of the system, thereby reducing the output voltage offset caused by the common-mode input voltage.

$$V_{n1}^2(rms) = e_{n1}^2 \cdot \left(1 + \frac{2 \cdot R_2}{R_1}\right)^2 + (i_{n1}^2 \cdot R_2)^2 + e_{nR2}^2 + \left(\frac{e_{nR1}}{\sqrt{2}} \cdot \frac{R_2}{R_1}\right)^2 \tag{3}$$

$$V_{n3}^2(rms) = [e_{n3} \cdot \left(1 + \frac{R_4}{R_3}\right)^2 + 2 \cdot (i_{n3} \cdot R_4)^2 + e_{nR4}^2 + \left(e_{nR3} \cdot \frac{R_4}{R_3}\right)^2 + \left[e_{nR34} \cdot \left(1 + \frac{R_4}{R_3}\right)\right]^2 \tag{4}$$

The output noise of the three-op-amp instrumentation amplifier can be analyzed by separating the input stage and the output stage, first performing gain analysis, and then performing noise analysis. The calculation method of the output noise spectral density of amplifiers A1 and A2 is shown in Equation (3), and the Equation (4) explains how to calculate the noise spectral density of the output stage, where the e_{n1}, e_{n2}, and e_{n3} is the input voltage noise spectral density of amplifier A1, A2 and A3 in Fig. 1, i_{n1}, i_{n2}, and i_{n3} is the input current noise spectral density of amplifier A1, A2 and A3, $\mathrm{e}_{\mathrm{nR1}}$, $\mathrm{e}_{\mathrm{nR2}}$, $\mathrm{e}_{\mathrm{nR3}}$, and $\mathrm{e}_{\mathrm{nR4}}$ is the thermal noise spectral density of resistor R1, R2, R3 and R4, $\mathrm{e}_{\mathrm{nR34}}$ is the thermal noise spectral density of resistors R3 and R4 connected in parallel. The total output voltage noise spectral density can be obtained by the sum of the squares of the three squares.

IV. Experiment Setup and Result

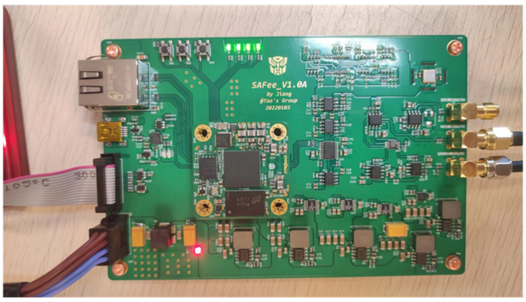

Fig. 2. Low noise front-end electronics SAFee testing.

Seven types high-voltage, high-bandwidth, and low-noise operational amplifiers from ADI were selected for early performance comparison and functional verification. Based on the key parameter calculation method explained in section III, we finally selected LT6018 [1] as the model of the A1, A2 and A3 amplifier in Fig. 1. Besides, ADI's LT5401 precision matched resistor network was selected to replace R3 and R4 in Fig. 1 to improve the CMRR of the system. Fig. 2 shows the actual object of SAFee.

The performance of SAFee front-end electronics was tested by WavePro HD high definition oscilloscope from TELEDYNE LECROY. The test results show that the output noise of SAFee is 150.34±1.13 μV RMS, which can meet the measurement requirements of solid-state pulse modulators with a stability of 50 ppm. In addition, the output voltage and DAC code are scaled, and the goodness of fit R^2 can reach more than 0.999999998, as shown in Fig. 3.

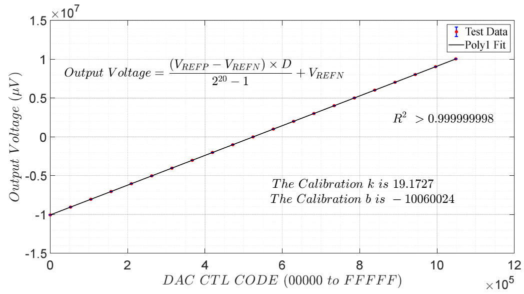

Fig. 3. Scale at -10V to 10V output.

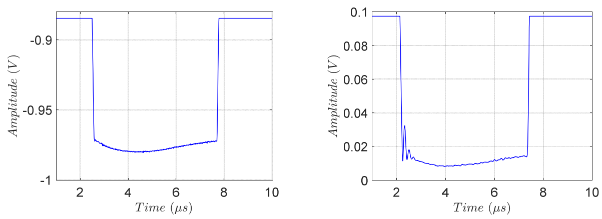

Fig. 4. Pulse signal with -1V offset measured by oscilloscope (left) and the output of the -1V biased pulse signal adjusted to 0 V by SAFee.

Tektronix's AFG3252C signal generator is used to generate an analog pulse signal. Fig. 4 shows the waveform before and after SAFee bias adjustment. After clamping the voltage of -0.5 V~0.5 V on the bias-adjusted output, the oscilloscope resolution can be adjusted to 1 mV/div to perform low-noise measurements.

V. Conclusion

This paper developed the ultra-low noise front-end electronics "SAFee" for pulse bias regulation. The measured output noise is 150.34 ± 1.13 μV, which can meet the 50 ppm accuracy measurement requirements.

Acknowledgment

We are grateful for the patient help of Yu Xue, Wenping Xue, and Jianfeng Zhang. They are seasoned full-stack hardware technologists with a wealth experience of in solder and rework in the electronics workshop at DEP.

References

[1] Analog Devices, Inc., LT6018 33V, Ultralow Noise, Precision Op Amp. [Online]. Available: https://www.analog.com/en/products/lt6018.html.