

# A Low-Noise, Large-Dynamic-Range-Enhanced Amplifier Based on JFET Buffering Input and JFET Bootstrap Structure

Haijun Zhou, Wenzhe Wang, Chaoyong Chen, and Yaohui Zheng

**Abstract**—We design a low-noise, large-dynamic-range amplifier based on transimpedance amplifier (TIA) for detecting shot noise of 1064-nm laser in quantum optical experiments. Compared with a single-junction field-effect transistor (JFET) buffered TIA, the electronic noise is effectively 2.8 dB suppressed at the analysis of 2 MHz, and 4 dB suppressed at 4 MHz by means of a JFET bootstrap structure. Under the transimpedance gain of 200 k $\Omega$  and 0.5 pF, the measured shot noise at the injected laser power of 51  $\mu$ W is 12.5 dB above the electronic noise at 2 MHz, and 9.8 dB at 4 MHz. With adjustment of bias condition of the bootstrap structure and application of a L–C (inductance and capacitance) structure, the dynamic range is largely boosted from the original 1.52 to 11.22 mW. The amplifier meets the requirement of SNR for Bell-state detection in quantum optical experiments.

**Index Terms**—TIA, low noise, large dynamic range, JFET buffering, JFET bootstrap, L–C structure, Bell-state detection, quantum optical experiments.

## I. INTRODUCTION

WITH the advance of quantum optics experiments, the need to measure the degree of entanglement and squeezing in large scale becomes increasingly important. Typically, the measured optical noise should be much higher than the electronic noise, i.e. large signal-to-noise ratio (SNR) of 10 dB or more at the analysis frequency of 2.0 MHz for a certain input laser power [1]–[4]. Conventionally, the SNR could be enlarged by boosting the current-to-voltage gain, increasing the input laser power, or equivalently by reducing the electronic noise at the analysis frequency of 2.0 MHz [3]–[6].

The need for low noise amplifier becomes even more urgent for optical Bell-states detection, where weak laser power of 50  $\mu$ W at the wavelength of 1064 nm could be extracted from the optical parameter amplifier (OPA) [2], [4]. Therefore, the optical noise or its squeezing and entanglement

could be easily overwhelmed by the electronic noise at the interested 2.0 MHz. Limited by available laser power, much efforts have been focused on reducing electronic noise of amplifiers in quantum optics experiments [1], [3], [4].

In order to gain large SNR and high available bandwidth, the transimpedance amplifier (TIA) have been widely used to convert current to voltage from photodiodes. However, one of critical challenges is that the input voltage noise of the op amp in the TIA would experience high-frequency noise voltage gain. So as to avoid this noise gain, it is necessary to keep the input voltage noise as small as possible, or equivalently to keep the photodiode capacitance as small as possible [3]–[10].

In this paper, considerations of each stage are analyzed with particular emphasis on noise performance for our amplifier. As a JFET buffering input and another JFET bootstrap structure could be independently applied to reduce the electronic noise of TIA with large input capacitance. Therefore, we propose the integration a JFET bootstrap structure into a JFET buffering input TIA to further reduce electronic noise. Meanwhile, in order to enlarge response dynamic range, a L–C structure is applied to lead the shot noise current (ac current) and the photocurrent (dc current) to be independently amplified in different loops. Subsequently, a single-frequency Nd:YVO<sub>4</sub> laser at 1064 nm with coherent output is applied to verify the amplifier performance.

Experimentally, the electronic noise is 2.8 dB suppressed at the analysis frequency of 2.0 MHz and 4.0 dB suppressed at 4.0 MHz respectively by the JFET bootstrap structure. When the injected laser power is around 51  $\mu$ W, the shot noise power is 12.5 dB higher than the electronic noise power at 2.0 MHz, and 9.8 dB at 4.0 MHz respectively under the transimpedance gain of 200 k $\Omega$  and 0.5 pF. Compared with the former Bell-state photodetector [4], even the SNR at 2.0 MHz is 0.5 dB smaller, the SNR at 4.0 MHz is largely boosted from the original 6.0 dB to the higher 9.8 dB. In addition, the dynamic range is largely extended from the original 1.52 mW to 11.22 mW in our new amplifier. Therefore, our amplifier could be applied to the detection of squeezing and entanglement in optical Bell-states, as well as relative researches, i.e., weak signal detection.

## II. SCHEMATIC OF THE AMPLIFIER

In order to amplify weak current, low noise and high input impedance enhanced TIAs are widely applied [5]–[8]. For the optical Bell-states (the laser power is 50  $\mu$ W), the shot noise

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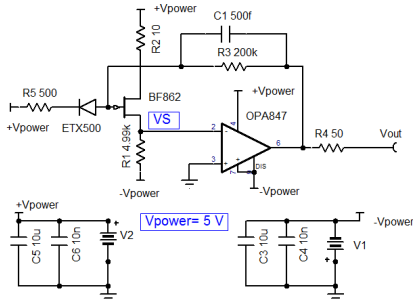


Fig. 1. The C-TIA with discrete JFET input at unity gain.

current could be estimated to be several picoamperes (pAs), which is comparable to input current noise of bipolar junction transistor (BJT) input op amps, i.e. the OPA847. Thus the shot noise current may be overwhelmed or overlapped by the high input current noise of BJT input op amps [3]–[5]. This is the reason why BJT input op amps are rarely used in applications calling for high SNR. Even the input voltage noise of a JFET input op amp seems quite higher than BJT one, the low input current noise (several fAs) facilitates the detection of ultra weak current and is extensively implemented [9]–[12].

In order to reduce the high-frequency noise voltage gain for TIAs with a large area, high capacitance photodiode (more than several tens of pF), it is necessary to have both low voltage noise and low current noise to achieve lower total noise [10]–[12]. Limited by available commercial low noise JFET input op amps, it becomes increasingly important to design amplifiers with JFET pre-amplifier along with a low noise BJT input op amp [10]–[12]. The circuit of Fig. 1 shows a low noise enhanced C-TIA connected to a high capacitance photodiode.

#### A. The Primary Composite-Transimpedance Amplifier (C-TIA)

One of the main stages of our amplifier is a composite transimpedance amplifier (C-TIA) shown in Fig. 1, consisting of the photodiode (ETX500), the discrete JFET-input buffer (BF862), and the low noise op amp (OPA847) [13]–[15].

The ETX500 is widely selected to measure squeezing and entanglement for its high quantum efficiency at 1064 nm, only with high junction capacitance of 35 pF even reverse biased at +5 V [4], [5], [13]. When the ETX500 is applied in TIA, efforts should be paid to high-frequency voltage noise gain [16]–[18]. The BF862 has high input impedance, low input voltage noise density (0.8 nV/sqrt(Hz)) at 100 kHz) with input capacitance around 9 pF in typical. And the OPA847 is selected for high gain bandwidth product of 3.8 GHz and low input voltage noise density (0.85 nV/sqrt(Hz)) at 100 kHz).

Compared to a standard TIA, the input impedance of the C-TIA is largely boosted because the BF862 acts as a source follower buffering the inverting input of the OPA847 [10]–[12]. As the pre-amplifier BF862 works at unity gain, the total input noise is effectively split between the JFET buffer and the op amp. Even lower noise could be scaled when some initial gain is applied to the JFET buffer, stabilizing the output is a challenge as shown in many applications [10]–[12].

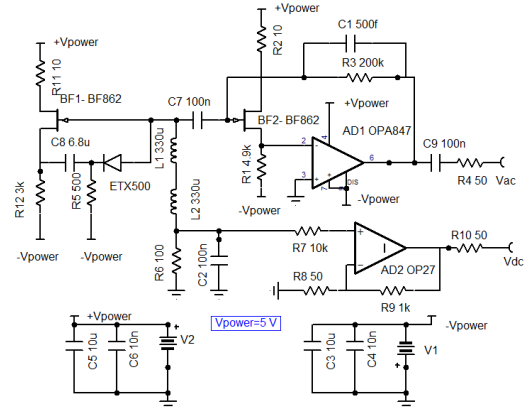


Fig. 2. The schematic of our amplifier based on the JFET buffer input and JFET bootstrap structure. The OP27 is powered by  $\pm 15$  V.

In order to avoid this, very low noise could be achieved when the JFET buffer still runs at unity gain only with strict demand for low noise op amps, i.e. the OPA847. Moreover, the transimpedance gain ( $R3=200$  k $\Omega$ ,  $C1=0.5$  pF) benefits from the low input noise current of the JFET, which is on the contrary prohibited for a single OPA847 based TIA [9]–[12].

In Fig. 1, the OPA847 forces the BF862 source voltage to be 0 V, with R1 ensuring that the BF862 runs at a drain current of 1mA and self-biases just below ground, i.e.  $V_G = -0.6$ V. As the BF862 is double powered, the BF862 source is not grounded but looks into the R1 and the input impedance of OPA847 [10], which could alleviate its input capacitance (estimated as 4.0 pF). When the ETX500 is illuminated, the current flow through the R3 and C1, as in a normal TIA.

#### B. The Amplifier With JFET Bootstrap Structure

Even the C-TIA is devised for both low input voltage noise and low input current noise, the high-frequency voltage noise gain could dominate the total output noise, as in a normal TIA [16]–[19]. In order to enlarge the SNR, much effort has been put onto reducing the voltage noise gain.

For TIA with large input capacitance, a bootstrap structure is originally intended for input capacitance reduction and for enhancing bandwidth [4], [19]–[27]. The principle of bootstrapping is to apply a buffer amplifier to keep voltages on both sides of the photodiode be the same. By doing so, no voltage difference appears on the photodiode. Thus the junction capacitance of the photodiode is effectively replaced by smaller input capacitance of the buffer amplifier, and the overall bandwidth of the TIA is increased. Therefore, we integrate the bootstrap structure into the C-TIA to investigate the reduction of electronic noise for the TIA based amplifier with a high capacitance photodiode.

The bootstrapped C-TIA includes two stages: the JFET buffer amplifier, and the C-TIA. Hence, the circuit diagram of the amplifier is shown in Fig. 2, which comprises three blocks: the ETX500 with a bootstrap structure, the ac-coupled C-TIA to measure the shot noise current, and the dc-loop of the photocurrent-to-voltage amplifier.



Fig. 3. Photograph of the amplifier. Many components are surface mounted (packaged in 0805), and the output connectors are all 50  $\Omega$ -BNCs.

The bootstrap structure is implemented by the BF1-BF862 along with the ETX500. And the capacitor-resistor pair (C8 and R12) is applied to enable the ac benefit of bootstrapping while allowing a reverse-bias voltage of +5 V onto the ETX500 through the bias resistor R5 [4], [10], [23]. During the test, the electronic noise differs with the change of bias conditions for both the BF1-BF862 and the ETX500. In order to extend the response dynamic range and lower the electronic noise, we adjust the bias resistor R5 of the ETX500 from the original 5 k $\Omega$  to 500 $\Omega$ , and the bias resistor R12 of BF1-BF862 from the original 5 k $\Omega$  to 3 k $\Omega$ .

In order to overcome dc-saturation effect caused by the high feedback resistor ( $R3 = 200$  k $\Omega$ ), the dc current and the ac current are guided to be separately amplified. Suggested by photodetector designs in quantum optics, the L-C (inductance and capacitance) facilitates the different amplifications [4], [5]. Based on components' high frequency performance, the L-C combination is implemented by the ac-coupling capacitor C7 (100 nF) and two similar dc-coupling inductor L1 and L2 (both valued 330  $\mu$ H,  $Q = 19$ ). The shot noise current is ac-coupled through the capacitor C7 into the feedback impedance ( $R3$  &  $C1$ ) with  $V_{ac}$  converted. As the output of the C-TIA sits at a certain dc voltage (0.6 V) even not illuminated, the output of the C-TIA is further ac-coupled through the capacitor C9.

As for the dc-amplification loop, the OP27 is still selected for its negligible offset voltage and offset current. The dc and audio frequency photocurrents travel through inductors L1, L2 and resistor R6 with a dc-voltage generated. And the dc-voltage is further amplified with a gain of 21 to provide a dc-voltage ( $V_{dc}$ ) for alignment, etc.

In order to minimize parasitic capacitances, a double-sided printed circuit board (PCB) is designed, as shown in Fig. 3. Nearly all components are soldered on the surface layer of the PCB and all tracks are kept as short as possible under principle of high frequency board layout. As the upper layer of the PCB is mainly used as signal traces, the ground planes around the OPA847, BF862, and OP27 are removed to minimize parasitic capacitances. The back side of the PCB is reserved as a whole ground plane (not shown) with fewest discontinuities.

Different from the schematic, some unsoldered pads are used for debugging, and the OP27 is powered by

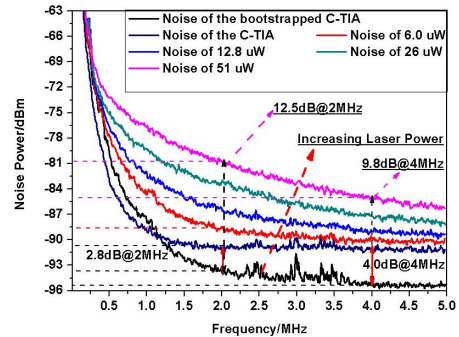


Fig. 4. Comparisons of electronic noise power VS. shot noise power, under the same ETX500 and the same 200 k $\Omega$  and 0.5 pF. Noise power is measured by the spectra analyzer (Agilent, N9020A), with RBW = 39 kHz, VBW = 30 Hz, and sweep time = 10.5 s. And a microwatt-ranged laser power meter from Thorlabs (S122C) is applied.

TABLE I  
CALCULATIONS VS. MEASUREMENT RESULTS (AT 2.0 MHz)

Elements	$C_{in}$ /pF	$E_{th}$ /nV	$E_n$ /nV	$E_{tot}$ /nV	Measured $E_{tot}$ /nV
C-TIA	39	32.5	59.7	68.0	31.0
Bootstrapped C-TIA	6.0	32.5	10.2	34.0	22.4

The  $E_{th}$ ,  $E_n$ ,  $E_{tot}$  represent thermal noise voltage of feedback impedance, amplified noise voltage of input noise voltage, and total output noise voltage, respectively. The measured  $E_{out}$  is deduced from measured results.

a noise-filtered homemade  $\pm 15$  V DC power. After voltage conversions by the LM7805 and LM7905, the bootstrapped C-TIA is powered by  $\pm 5$  V DC. And the amplifier is shielded by a cast-aluminium box to avoid other noises.

### III. RESULTS OF THE AMPLIFIER

#### A. Characteristic of Electronic Noise and Gain

Noise performances between the bootstrapped C-TIA and the single C-TIA are compared in Fig. 4, i.e. the bottom two curves. At the analysis frequency of 2.0 MHz, 2.8 dB reduction of the electronic noise could be achieved by the bootstrap effect, i.e., from the original  $-91.0$  dBm (not bootstrapped) down to the  $-93.8$  dBm (bootstrapped). And at 4.0 MHz, the electronic noise is suppressed at the level of 4.0 dB with much lower electronic noise. Due to the insufficient noise reduction, the SNR at 2.0 MHz is slightly lower (12.5 dB VS.  $-13.0$  dB) than the former Bell-state photodetector under the same 51  $\mu$ W laser and the same transimpedance gain [4]. However, for our new amplifier, the SNR at 4.0 MHz is much higher (9.8 dB VS. 6.0 dB). This merit ensures that detection of large-scaled squeezing and entanglement could be performed at 4.0 MHz as well, which is prohibited on the contrary for the former one [4]. Therefore, the new bootstrapped C-TIA performances better for Bell-state detection.

According to the noise analysis of TIA [3], [18], theoretical calculations and measured results are listed in Table I. For the C-TIA, the input capacitance ( $C_{in} = 39$  pF) is a summation of the junction capacitance of the EX500 (35 pF), the intrinsic input capacitance of the C-TIA (4.0 pF). On the contrary, for the bootstrapped C-TIA, the input capacitance ( $C_{in} = 6.0$  pF)

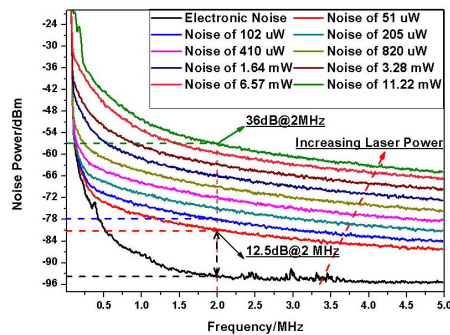


Fig. 5. Response dynamic range of the amplifier with the input laser power double varied. Settings of the spectra analyzer are kept the same as in Fig. 4.

is the summed gate capacitance of the BF1-BF862 (2.0 pF) and the intrinsic input capacitance of the C-TIA (4.0 pF) suggested by the bootstrap effect. Given parasitic capacitances from R3, C1, and PCB, the feedback capacitance (C1) is about 0.8 pF. And the input noise voltage of the C-TIA could be estimated to be 1.20 nV at 100 kHz.

In the case of the C-TIA, the total output noise voltage ( $E_{tot}$ ) is dominated by the amplified noise voltage ( $E_n$ ) due to large input capacitance ( $C_{in}$ ). For the bootstrapped C-TIA, the total output noise voltage ( $E_{tot}$ ) is dominated by the thermal noise voltage ( $E_{th}$ ) of the feedback impedance (R3 & C1). In theory, this means that even the bootstrap structure is aimed to reduce input capacitance (39 pF VS. 6.0 pF), the thermal noise sets a noise floor and does restrict the reduction of electronic noise.

However, limited by inaccurately estimated capacitance of the ETX500 and other parasitic capacitances, calculated noise voltages are much larger than those measured. And measured noise voltages also indicate that total output noise voltages may be partially attenuated by the low pass effect of the feedback impedance (R3 & C1) at 2.0 MHz. Even so, the trend between calculations and measured ones keep the same and demonstrate the noise reduction of bootstrap structure.

Subsequently, a single-frequency Nd:YVO<sub>4</sub> laser at 1064 nm with coherent output is applied to verify characteristics of high gain and large dynamic range [4]. When a weak laser of 51  $\mu$ W is focused onto the ETX500, the measured shot noise power is 12.5 dB larger than the electronic noise power at 2.0 MHz and 9.8 dB at 4.0 MHz. In particular, the shot noise power of 6.0  $\mu$ W laser is nearly indistinguishable with the electronic noise power of the single C-TIA. However, as for the bootstrapped C-TIA, the shot noise power is still 4.0 dB higher than the electronic noise power at 4.0 MHz.

### B. Response Dynamic Range

As shown in Fig. 5, a clearance of 3 dB at 2.0 MHz could be achieved when the laser power is double increased from 51  $\mu$ W to 11.22 mW. The measured clearance of 3 dB at 2.0 MHz does demonstrate that the input laser is coherent. At 2.0 MHz, it should be also noted that the amplifier presents not only a SNR of 12.5 dB for 51  $\mu$ W laser, but a maximum SNR of 36.0 dB for 11.22 mW laser. Limited by dc saturations and variations of bias condition of the ETX500,

there exist some inaccuracies in linearity for laser power around 11.22 mW. In comparison to the former one [4], the dynamic range is largely extended from the original 1.52 mW up to the 11.22 mW. Therefore, our amplifier meets the SNR requirement of optical Bell-state detection.

## IV. CONCLUSION

In conclusion, we describe and analyze the design proposal, and performance of an electronic noise lowered, and response range enhanced amplifier for shot noise detection in quantum optics experiment. By integrating a JFET bootstrap structure into a JFET buffered C-TIA, the electronic noise is effectively 2.8 dB suppressed at the analysis frequency of 2.0 MHz, and 4.0 dB suppressed at 4.0 MHz. With the transimpedance gain of 200 k $\Omega$  & 0.5 pF, the measured shot noise of 51  $\mu$ W laser (1064 nm) is 12.5 dB above the electronic noise at 2.0 MHz, and 9.8 dB at 4.0 MHz, which exceeds the requirement of SNR for optical Bell-states detection. With parameters adjusting of the ETX500 and the L-C combination, the response dynamic range is largely extended from original 1.52 mW up to 11.22 mW. The new amplifier could not only be applied in optical Bell-states detection, but in a wide variety of applications, i.e., weak signal detection.

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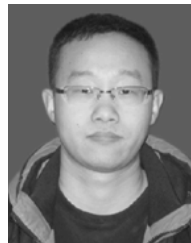
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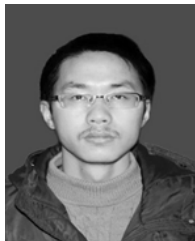
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