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REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 013111 (2014)

A bootstrapped, low-noise, and high-gain photodetector for shot noise measurement

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We presented a low-noise, high-gain photodetector based on the bootstrap structure and the L-C (inductance and capacitance) combination. Electronic characteristics of the photodetector, including electronic noise, gain and frequency response, and dynamic range, were verified through a single-frequency Nd:YVO$_4$ laser at 1064 nm with coherent output. The measured shot noise of 50 μW laser was 13 dB above the electronic noise at the analysis frequency of 2 MHz, and 10 dB at 3 MHz. And a maximum clearance of 28 dB at 2 MHz was achieved when 1.52 mW laser was illuminated. In addition, the photodetector showed excellent linearities for both DC and AC amplifications in the laser power range between 12.5 μW and 1.52 mW. © *2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4862295]

I. INTRODUCTION

The measurement of optical noise at the shot noise limit sensitivity with photodetector is an essential part of many quantum optics experiments, especially in nonclassical-light generation,[1,2] continuous variable (CV) quantum teleportation, and quantum information.[3,4] Quantum noise is usually measured through balanced homodyne detection (BHD) or heterodyne detection and could be typically compared with the shot-noise level of coherent light at the same power.[5,6] The dark current of the photodiode, thermal noise of resistors, and the current and voltage noise in the op amps are the major contributors towards electronic noise when no light is incident on the photodiode, which sets a strong limitation to the measurement of quantum noise.[7,8] The level that shot noise should be above the electronic noise is dependent upon the amount of squeezing and entanglement one wishes to measure. In order to measure strong squeezing and entanglement, photodetectors should meet the condition that the measured level of shot noise should be much higher than the electronic noise, typically 10 dB or more.[9,10] This condition can be achieved by increasing the signal power, boosting the detector gain, and reducing the electronic noise as much as possible.

In the experimental process based on the BHD, weak signal beam is composited on a 50/50 splitter with a strong local oscillator, typically several milliwatt, resulting that the shot-noise level exceeds the electronic noise in large scale.[9,11] This method lowers expectation to low-noise, high-gain photodetectors. However, in the experimental setup for multipartite entanglement and quantum teleportation,[12,13] the BHD requires a local oscillator as auxiliary beam for every signal. Without doubt, this measurement will add system complexity with more optical arrangements are required.

Bell-state detection (BSD)[6,14,15] is another effective way of detecting quantum noise, which directly separates the signal beam from optical parameter oscillator (OPO) and measures the quantum noise through a 50/50 splitter without the local oscillator. However, the main shortcoming is that the signal beam is rather weak, typically at the power level of 50 μW. Thus the shot noise current of 50 μW signal beam could be easily overwhelmed by the electronic noise of the photodetector (usually measured at 2 MHz). By contrast, the method of BSD puts a stringent demand for low-noise, high-gain photodetector.[6,16] Therefore, how to make the clearance between shot noise and electronic noise be larger than 10 dB at weak power seems quite a challenge for BSD.

In this paper, we developed a low-noise, high-gain photodetector based on the bootstrap structure, and adopted L-C (inductance and capacitance) combination to extend the dynamic range of photodetector. Subsequently, a single-frequency Nd:YVO$_4$ laser at 1064 nm with coherent output was applied to verify electronic characteristics of low noise, high gain, and large dynamic range of the photodetector. The measured shot noise of 50 μW laser was 13 dB above the electronic noise at the analysis frequency of 2 MHz, and 10 dB at 3 MHz. A maximum clearance of 28 dB at 2 MHz was achieved when 1.52 mW laser was illuminated. The dynamic range was from 12.5 μW to 1.52 mW, with linear amplifications for both DC current and AC current achieved. The photodetector is suitable for detecting weak optical signal in the microwatt range, which will greatly prompt the quantum optics, as well as the relative research work.

II. PHOTODETECTOR DESIGN

A. Design principles

Even shot noise is a quantum noise effect, which is related to the statistical fluctuation of the mean photons detected by the detector (photodiode, in typical), it could be viewed as a noise current.[16–18] Thus shot noise current (AC current) could be detected as a noise voltage (AC voltage) across a load resistance, and mean photocurrent (DC current) be measured as a DC voltage.[19,20] In an approximate sense, a

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photodiode can be regarded as a current source for the photocurrent, the shot noise current (neglecting shot noise current of dark current), and other noise current.

Transimpedance amplifier (TIA) offering the potential of lower noise and larger bandwidth than a termination resistor and a voltage amplifier, is widely applied to convert the shot noise current to an AC voltage.[21,22] However, compared to the mean photocurrent, the shot noise current is rather weak and could be easily overwhelmed by the electronic noise. Even TIA is an effective method to measure noise current, the large capacitance of the photodiode along with the amplifier input capacitance (several pF) and other parasitic capacitances, could lead to high-frequency noise peaking.[18,22] Theoretically, the equivalent input voltage noise experiencing noise-gain could dominates in the electronic noise. Designing to make the shot noise visible is just as difficult as designing to minimize the electronic noise, which puts more stringent requirement upon the photodetector.

The photodiode ETX500 (large active diameter of 0.5 mm, InGaAs PIN photodiode from JDSU) is a popular selection for its high responsivity in the 800–1700 nm spectra with negligible dark noise.[9,13] The main restriction is that a high junction capacitance, 35 pF in typical, exists even reverse biased at 5 V. This large capacitance strongly limits bandwidth of ETX500 to be several MHz when quantum noise measurements are performed in BSD or BHD. Especially, the weak shot noise current, typically 3 pA/$\sqrt{\text{Hz}}$ for 50 μW laser at the wavelength of 1064 nm, may be easily overwhelmed in the TIA structure.

Conventionally, there reaches a consensus that wideband, ultra-low noise, voltage-feedback op amp, such as OPA847 (TI Corporation), is an optimal choice for broadband and low-noise photodetectors. However, the high equivalent input current (3.5 pA/$\sqrt{\text{Hz}}$ at 1 MHz) could alone overwhelm the shot noise current of 50 μW laser, especially for application of high gain or high input capacitance.[23] Thus the OPA847, and other low-noise amplifiers with bipolar junction transistor (BJT) inputs could only function well for broadband and low gain applications. However, low noise op amps with junction field-effect transistor (JFET) inputs are preferred for high gain applications, which make measurements of optical noise at low light intensities be possible.[24,25] Even the equivalent input current noise is extremely low or negligible, most op amps with JFET inputs show rather high equivalent input voltage noise, which demands some more attentions for photodiode with a high input capacitance.[25–27]

B. The standard TIA and response

To be a comparison, we tested the photodetector response in the standard TIA structure (the schematic is not shown here) with the photodiode ETX500 DC-coupled to a low noise op amp ADA4817-1 (low noise, high speed voltage feedback op amp with junction field-effect transistor (JFET) inputs).[27] In order to obtain high gain in the TIA, a feedback resistance of 200 kΩ (0805 ceramic SMT resistance with 1% precision, from VISHAY) and a compensation capacitance of 0.5 pF (0805 ceramic SMT capacitor with ±0.1 pF precision, from MURATA) were applied. Due to severe DC saturation effect for such high gain, the input laser power was limited to 25.5 μW or less. Figure 1 showed that the clearance between the shot noise and the electronic noise was only 1.4 dB at 2 MHz when 12.5 μW laser (single-frequency Nd:YVO$_4$ laser at 1064 nm) was illuminated. It was obvious that both the electronic noise of the photodetector and shot noise were far larger than the noise floor of the SA. Surprisingly, even the feedback resistance was rather high, the measured shot noise was rather weak and becoming nearly indiscernible or immeasurable. Obviously, the relative high DC voltage could suffer the weak shot noise voltage with the measurement of shot noise seems troublesome. Therefore, the DC-coupled TIA not only put a strong restriction to the photodetector response dynamic range, but posed difficulty to the measurement of Bell-state.

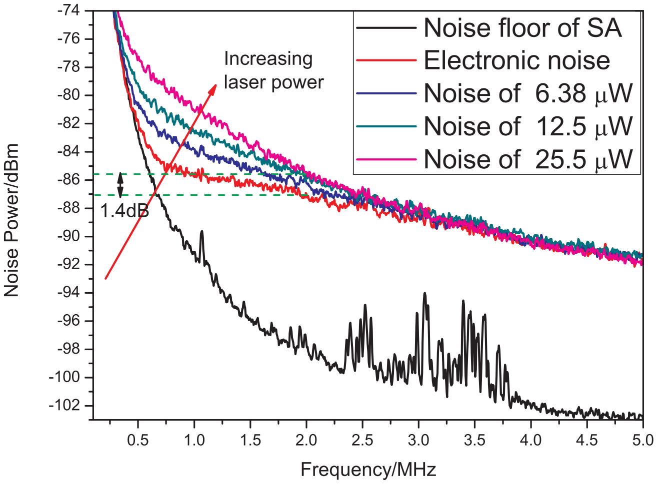

FIG. 1. Measured noise power of the standard (DC-coupled) TIA for different powers of laser. More information about the printed circuit board (PCB) and noise analysis was mentioned in the following. A calibrated laser-power meter from Thorlabs (S122C power head) was applied to measure the microwatt laser. And noise power was measured by the spectra analyzer (Agilent, N9020A, shorted as SA), with parameters set as RBW = 39 kHz, VBW = 30 Hz, and sweep time = 10.5 s.

C. The new photodetector

However, the bootstrap structure suggested in the LTC6244 application,[28–30] not only let the equivalent input voltage noise (8 nV/$\sqrt{\text{Hz}}$ at 100 kHz) of the LTC6244 be replaced by the (1 nV/$\sqrt{\text{Hz}}$ at 100 kHz) of the BF862 (a high transition frequency (715 MHz), ultra-low noise Junction Field-effect Transistor),[31] but let the bandwidth be slightly improved as the bootstrapped TIA enables a reduction of the compensation capacitance. Therefore, we tended to apply the bootstrap structure, with the benefits of low noise, high gain further enhanced.

Even though multiple JFETs in parallel could further improve bootstrapping with lower noise,[28,29] we sticked to adopt only one for stable operation in quantum optics experiments, where any circuit fluctuation could lead measured results to be invalid. As Figure 1 showed that the shot noise of 12.5 μW laser with the gain of 200 kΩ could be suffered from DC saturation effect in the DC-coupled TIA with or without

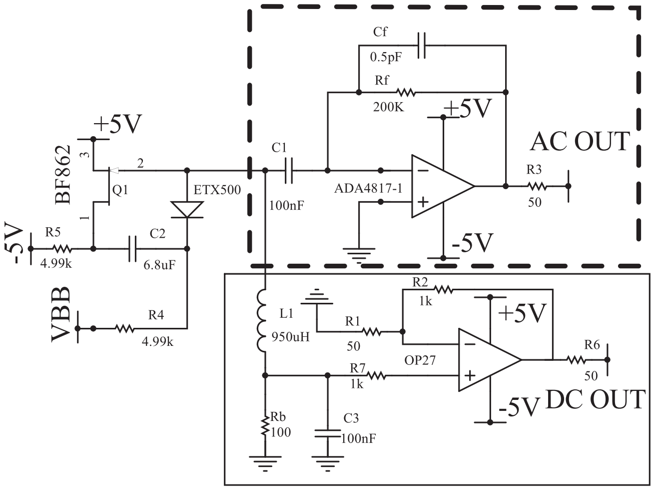

FIG. 2. The circuit diagram of the bootstrapped, low-noise, and high-gain photodetector. Filtering and bypassing of power supply were performed in advance. All components were used under principles of high-frequency applications.

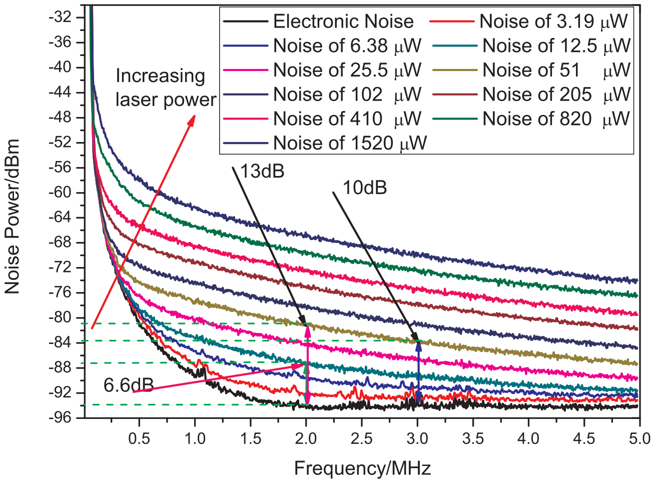

FIG. 3. Noise power measured for noise level comparison of different laser powers. With the laser power double varied, shot noise varied linearly by 3 dB. The setting of the spectra analyzer was kept the same as in Fig. 1.

bootstrapping. Hence how to separate the large DC current and the weak AC (shot noise) current before being separately amplified without oscillation is quite a challenge.

Experimentally, amplified DC and AC voltages should be observed separately with different gains are needed in Bell-state measurement, where the DC voltage is used as an error signal for phase locking and AC voltage as the level of shot noise. As suggested by photodetector design in quantum optics and Gravitational-Wave (GW) photodetectors,[10,17] the L-C (inductance and capacitance) combination facilitates the different amplifications. Thus the main circuit diagram for DC amplification and AC amplification is shown in Figure 2.

The bootstrap structure was implemented by one ultra low noise JFET BF862 before the low noise op amp ADA4817-1. The capacitor-resistor pair (C2 and R4) is used to enable the AC benefits of bootstrapping while allowing an arbitary reverse bias voltage (VBB) on the photodiode ETX500. For the laser power in the microwatt range, a VBB of +5 V should be enough to make the photodiode ETX500 be reverse biased. And the VBB should be synchronously tuned when the laser power was several milliwatts.

In the design of GW photodetector, the parallel L-C circuit acts as a current-to-voltage converter at the resonant frequency before a high voltage gain (30 dB, provided by op amp) is applied.[17] By comparison, in our AC-coupled TIA, due to the virtual earth at the negative input, the signal current (shot noise) is coupled through capacitance C1 into the virtual earth and through the feedback impedance to produce an AC voltage. It should be noted that the added inductor L1 not only shunts DC and audio currents, but attenuates electronic noise voltage at low frequencies. Therefore, both the shot noise voltage and the electronic noise voltage may be damped at low frequencies as shown in Figure 3. As the electronic noise in Figure 3 showed that two similar inductances of the same value (L = 475 μH, Q = 19) in series functioned best with least signal loss in the whole analyzed frequency range (2.0–5 MHz). Remember that a single inductance of L1, valued 950 μH (Q = 19) should not be used as its poor performance at high frequency. Experimentally, the AC coupling capacitance C1 should be higher and a 100 nF was selected with less high frequency impedance appeared.

To keep the bootstrapped TIA be of high speed and high GBP, we selected the ADA4817-1 rather than the original LTC6244. This op amp not only showed lower equivalent input voltage noise but lower input capacitance.[27,28] In the bootstrap structure, the excellent noise reduction is mostly due to the bootstrap effect of swapping the 1 nV/$\sqrt{\mathtt{Hz}}$ (at 100 kHz) of the JFET BF862 for the 4 nV/$\sqrt{\mathtt{Hz}}$ (at 100 kHz) of the ADA4817-1. However, the impact of equivalent input noise current of ADA4817-1 still functions. That is mainly why we preferred op amps with JFET inputs, instead of BJT inputs, such as OPA847.

In the AC amplification loop (dashed line area), in order to get highest clearance between the shot noise and the electronic noise, we still selected the combination of a feedback resistance 200 kΩ (0805 ceramic SMT resistance with 1% precision, from VISHAY) and a compensation capacitance 0.5 pF (0805 ceramic SMT capacitor with ±0.1 pF precision, from MURATA). As demonstrated in the standard TIA, a single stage TIA with such a high gain would be enough to measure shot noise for laser in the power level of microwatt. Parasitic capacitances and inductances should be avoided and minimized under the criterion of high-frequency transimpedance amplifiers.[32,33]

In the DC amplification loop (solid line area), a voltage amplifier OP27 showing negligible offset voltage or offset current was selected.[10] The DC and audio frequency photocurrents travelled through inductor L1 and resistor Rb. The voltage generated across Rb was then amplified without oscillation to provide a DC voltage used for both alignment and phase locking. For stable operation and demands in quantum optics experiments, DC voltage gain of 21 was preferred to obtain enough error signal for phase locking, etc.

Laying out the PCB is usually the last, but very critical step in the design process. Because the ADA4817-1 and BF862 can operate into the high frequency spectrum, high frequency board layout considerations should be taken into account. The PCB layout, signal routing, power supply bypassing, and grounding were all in strict accordance with the instruction of ADA4817-1 to ensure optimal performance. Especially, in the AC loop, all tracks around the TIA should be kept as short as possible, and the parasitic capacitances (inductances) between the inputs and ground should be minimized in case of oscillation.

III. EXPERIMENTAL RESULTS OF THE NEW PHOTODETECTOR

After well constructed, cleaned, and examined, the photodetector was shielded in a customized aluminum box. In order to prevent the crosstalk among the photodiode, amplifiers, and output ports, separated metal walls were applied.

First, a weak laser of 3.19 μW was sent to the photodetector, resulting a clearance of 1.6 dB between the shot noise and the electronic noise at 2 MHz. Theoretically, when the input laser was at the shot noise limit (only shot noise exists in the laser), double variation in the laser power could lead to 3 dB difference in the shot noise power.[16] Therefore, we let the laser power be double increased from 3.19 μW all the way to around 1.52 mW, with the DC voltages be monitored at the same time. As Figure 3 showed, the measured 3 dB difference at 2 MHz strongly supported that the input laser was shot noise limited at 2 MHz. All the results in Figure 3 were measured and verified several times. Especially, when the laser power was 50 μW, the photodetector demonstrated a clearance of 13 dB between the shot noise and the electronic noise at 2 MHz, and 10 dB at 3 MHz, which meant that the shot noise was larger than the electronic noise. Thus, a maximal squeezing of 13 dB could be expected for Bell-state measurement at 2 MHz, and 10 dB at 3 MHz. Furthermore, a maximum clearance of 28 dB at 2 MHz was achieved when 1.52 mW laser was illuminated. In order to test the needed laser power where the shot noise equals to the electronic noise, we made several trials to bring the input laser power down from 6.38 μW. However, limited by the fluctuation of laser power, the limited measuring-range of laser-power meter, and stray light in optics laboratory, it was difficult to make thus accurate measurement.

As stated in Figure 1, the electronic noise of standard TIA was around −87 dBm at 2 MHz with −85.6 dBm at 2 MHz for the shot noise of 12.5 μW laser (the clearance is 1.4 dB). However, the electronic noise of the improved photodetector was around −93.8 dBm at 2 MHz with −87.2 dBm at 2 MHz for the shot noise of 12.5 μW laser (the clearance is 6.6 dB). Therefore, it was obviously demonstrated that the equivalent input voltage noise of the op amp in the standard TIA set severe restrictions to the lowest shot noise that could be measured for such a high-gain application. Even through the bootstrapping structure suggested a noise reduction of factor 4 (4 nV vs 1 nV), the electronic noise of the bootstrapped photodetector was suppressed about 6.8 dB compared to the standard TIA. However, the clearance of the bootstrapped photodetector showed an increase of 5.2 dB (for 12.5 μW laser), hence the total improved clearance was around 12.0 dB (for 12.5 μW laser). And it was worth noting that the electronic noise was kept so flat and low below 5 MHz without noise peaking. As results of the low-pass of Cf and Rf, the frequency response of the photodetector was unflat, especially at 2 MHz or 3 MHz we valued most.

TABLE I. Analysis of linear response for AC and DC amplification loops when laser power was double increased from 3.19 μW to 1.52 mW, Here the "ΔClearance" meant the difference between two noise powers at 2 MHz, and "ΔDC" meant the ratio of the two DC voltages when the laser power was doubled.

Power (μW)	Clearance (dB)	Δ Clearance (dB)	DC (mV)	ΔDC
3.19	1.6	⋯	1.8	⋯
6.38	4.3	2.7	6	3.33
12.5	6.9	2.6	14	2.33
25.5	10	3.1	31	2.215
51	13	3	62	2
102	16	3	134	2
205	19	3	274	2.04
410	22	3	556	2.03
820	25	3	1070	1.92
1520	28	3	2020	1.89

Furthermore, we compared the DC linearity and AC linearity in Table I. Due to the difficulty to make accurate laser-power measurement around the 6.38 μW, there existed some inaccuracy in linearities in this range. Therefore, as the input laser power double changed, both the DC linearity and AC linearity could be reached between the 12.5 μW and 1.52 mW. The clearance of 13 dB for 50 μW supported that the new photodetector could meet the demands of measurement of Bell-state. In next stage, we will construct two or four similar photodetectors for BSD and BHD in quantum optics experiments.

IV. CONCLUSION

In conclusion, we have developed a low-noise, high-gain photodetector based on the bootstrapped TIA technology and the combination of L-C (inductance and capacitance), which is suitable for measuring the shot noise of 1064 nm laser in the power range of microwatt. The designed photodetector had a large gain of 200×10^3 V/A for the shot noise current without the influence of large DC current. When illuminated by 50 μW laser, a clearance of 13 dB between the shot noise and the electronic noise was achieved at 2 MHz, and 10 dB at 3 MHz. With laser power double changed from 6.38 μW to 1.52 mW, excellent linearities for DC amplification and AC amplification were achieved. The developed photodetector could be easily constructed with more available components, and could be further used in Bell-state measurements.

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