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An excess noise measurement system for weak responsivity avalanche photodiodes

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Abstract: A system for measuring, with reduced photocurrent, the excess noise associated with the gain in avalanche photodiodes (APDs), using a transimpedance amplifier front-end and based on phase-sensitive detection is described. The system can reliably measure the excess noise power of devices, even when the un-multiplied photocurrent is low (~10 nA). This is more than one order of magnitude better than previously reported systems and represents a significantly better noise signal to noise ratio. This improvement in performance has been achieved by increasing the value of the feedback resistor and reducing the op-amp bandwidth. The ability to characterise APD performance with such low photocurrents enables the use of low power light sources such as light emitting diode rather than lasers to investigate the APD noise performance.

Keywords: avalanche photodiode, excess noise, noise measurement.

1 Introduction

Impact ionisation provides internal current gain in avalanche photodiodes (APDs), which are often used to improve the signal-to-noise ratio (SNR) of an optical receiver in communications, medical and military applications [1]–[3]. The maximum useful gain in APDs is ultimately limited by the excess noise generated by the stochastic nature of the avalanche multiplication process. This noise can degrade the overall SNR of the optical receiver at very high gain values. McIntyre's local noise model [4] showed that the when electrons initiate the ionization process, the ratio of the hole (β) to electron (α) ionization coefficients $k = \beta/\alpha$ is required to be much smaller than unity if the APD is to show low noise. Consequently, the measurement of the excess noise in APDs as a function of gain is often used to characterise their performance and to determine the optimum value of gain. It is also often used as a way of inferring the ionization coefficient ratio of the material system. The measurement of excess noise has usually been undertaken with a Noise Figure Meter (NFM) [5]. These suffer from the problem that they need a high photocurrent level relative to the dark current. Not only does this necessitate the use of fairly high power lasers, which often can add noise to the measurement by way of their relative intensity noise (RIN), the large photocurrents can result in device heating and also distortion of the electric-fields under which the APD operates [6]. If the excess noise measurements could be done at very low optical powers and hence photocurrents, LEDs could be used which avoid both of the aforementioned problems. The systems used by Bulman and Ando & Kanbe [7][8] required minimum primary photocurrents of 0.63 µA and 6.25 µA respectively for their measurements. Lau et al.[9] and Green et al. [10] reported measurement systems based on transimpedance amplifier front-ends. Lau et al. [9] reported that the excess noise factor could be measured on APDs with sub-micron depletion region widths, high dark currents, a capacitance of up to approximately 50 pF and required a minimum primary photocurrent of 0.22 µA. The latter system by Green et al. [10] was designed to reliably measure the excess noise factor of large area relatively low dark current devices with a capacitance of up to 5 nF and required a minimum primary photocurrent of 1 µA. The signal to noise ratios described by Lau et al. [9] has the most desirable SNR which is -25.7dB. In the work reported in [7]–[10], the photocurrents were modulated and phase sensitive detection techniques were used as this largely removed the impact of the dark currents of the APD.

In this paper we describe a measurement system which is capable of measuring the excess noise of an APD with a photocurrent as low as 10 nA, which is two orders of magnitude lower than our prior work [9][10]. The maximum capacitance is restricted to 22 pF but this is well with the range of most practical APDs of interest, with device diameters of up to 400 µm and total depletion widths that exceed 1 µm.

2 Noise measurement system

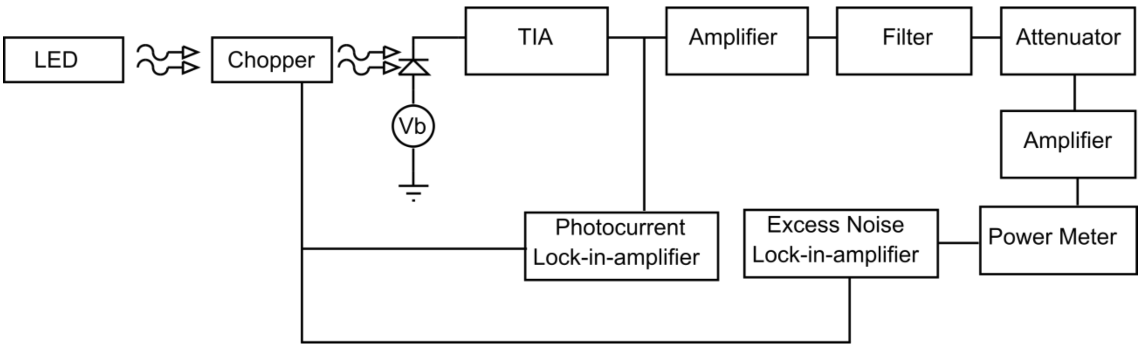

Figure 1**:** Block diagram of the excess noise measurement system.

The structure of the new measurement system is based on that of Lau et al [9] and is shown in figure 1. A signal generator and single transistor switching circuit is used to provide power to the LED which provides electrical "chopping" at 180 Hz and thereby provides a reference signal to the lock in amplifiers (LIAs) used in the phase sensitive detection. This becomes essential when the photocurrent being measured starts to decrease to the level of the device dark current. A Keithley 236 source measure unit (SMU) provides the reverse bias voltage, Vb, to the DUT. The transimpendance amplifier (TIA), which is based on the operational amplifier OPA656 with a gain of 100 kV/A (unterminated) is used to convert the total diode current into a voltage. Thereafter the voltage is amplified using the Minicircuits ZFL-500LN+ with a terminated gain of 27.98 dB. A precision stepped attenuator, HP 335D, is used to reduce the system gain from 0 dB to -120 dB in 10 dB steps if required. Before the noise information can be extracted, the photocurrent signal must first be removed using a cascade of single tuned Friend bandpass filters [11] with a bandwidth of 0.2 MHz, centred on 1 MHz. The narrow bandpass filter is chosen to minimise the other non-photogenerated noise sources. The centre frequency of 1 MHz is high enough to avoid 1/f noise [12]–[14], but low enough to lie within the bandwidth of the TIA. The noise signal is amplified by a second voltage amplifier, which is based on the AD829 operational amplifier with a terminated gain of 35.56 dB before entering a squaring and averaging circuit. The squaring and averaging circuit, which acts as a noise power meter, uses an Analogue Devices AD835 analogue multiplier. The output of the noise power meter is measured using the first lock-in-amplifier. The photocurrent signal is taken from the TIA and is measured by using the second lock-in-amplifier. Lau et al. [9] designed a transimpedance amplifier by using an Analog Devices AD9631 at 10 MHz with a 2.2 kΩ feedback resistor in order to optimise the bandwidth and gain of APDs with high capacitances. In more conventional optical communication systems, APDs have smaller device capacitances, so the new system can increase the gain to 100 k and reduce the bandwidth from 10 MHz to 1 MHz in order to obtain measurements derived from substantially reduced primary photocurrents compared to prior reports.

2.1 Transimpedance amplifier

The transimpendance amplifier (TIA) is shown schematically in figure 2. The TIA is based on the operational amplifier OPA656 [15] which is a wideband (500 MHz) unity gain stable voltage feedback amplifier. R_1, C_1, the junction capacitance of the APD (C_j) and the operational amplifier OPA656 gain bandwidth product (GBP) determine the useful bandwidth of the TIA. The APD junction capacitance is an effect of the depletion of carriers from the transition region due to the enhancement of the built in electric field by the external reverse bias voltage, Vb. C_j varies approximately with the inverse square of increasing bias voltage. R_1 is 100 kΩ in order to give a large transimpedance gain while maintaining the required bandwidth of the system. C_1 (0.4 pF) is chosen to maximise both transimpedance gain and bandwidth while minimising gain peaking across the range of Cj. The shot noise developed by 10 nA is 56.6 fA/$\sqrt{\text{Hz}}$ and as the bandwidth of this measurement system is 0.2 MHz, this corresponds to 25 pA noise current.

2.2 TIA noise performance

The noise performance of the transimpedance amplifier can be analysed using the stand opamp noise model which has an equivalent noise current source, I_n , and an equivalent noise voltage source, V_n. The equivalent noise model of the TIA is shown in figure 3. The output noise voltage from the input noise current from the op-amp is,

$$\frac{V_o}{I_n} = G(f) = -\frac{A_o r_d R_f}{(A_o r_d + R_f + r_d) + s(k + \tau_o r_d + \tau_o R_f + A_o C_f R_f r_d) + s^2 \tau_o k} \qquad (1)$$

Where $k = C_j r_d R_f + C_f r_d R_f$, R_f is the feedback resistance, C_f is the feedback capacitance, r_d and C_j represent the equivalent circuit of the APD, shunt resistance and junction capacitance, respectively. Assuming the op-amp open loop gain is given by the first order transfer function:

$$A_f = \frac{A_o}{1 + s\tau_o} \qquad (2)$$

A_o is the open loop gain of the op-amp and τ_o is the open loop time constant of the op-amp.

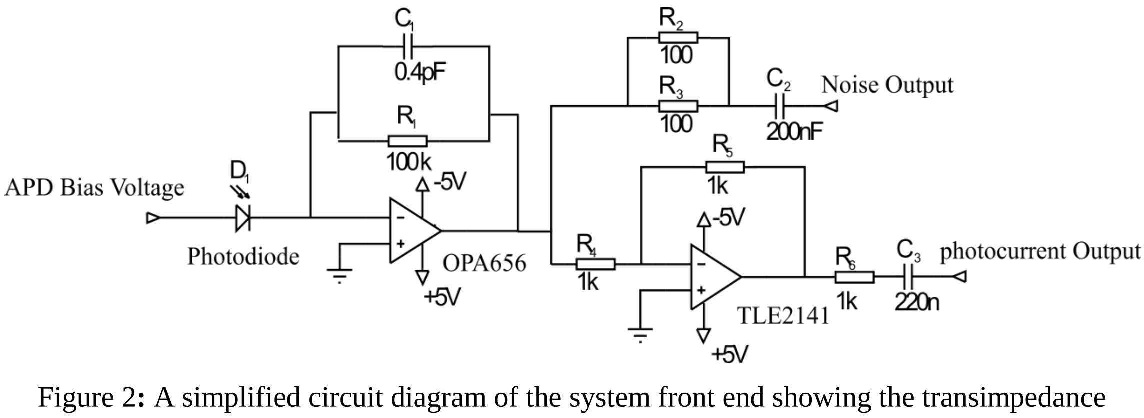

Figure 2**:** A simplified circuit diagram of the system front end showing the transimpedance amplifier (OPA656) and a buffer amplifier TLE2141.

The output noise voltage from the input noise voltage from the op-amp is,

$$\frac{V_o}{V_n} = -\frac{A_o(r_d + R_f) + skA_o}{(A_o r_d + R_f + r_d) + s(k + \tau_o r_d + \tau_o R_f + A_o C_f R_f r_d) + s^2 \tau_o k} \qquad (3)$$

The output noise voltage due to the thermal noise of the feedback resistance is,

$$\frac{V_o}{V_{nf}} = -\frac{A_o r_d}{(A_o r_d + R_f + r_d) + s(k + \tau_o r_d + \tau_o R_f + A_o C_f R_f r_d) + s^2 \tau_o k} \qquad (4)$$

The total noise voltage at the output from the input noise current, I_n, the input voltage noise, V_n and feedback thermal noise, V_{nf} is,

$$V_{on}^2 = \frac{I_n^2 (A_o r_d R_f)^2 + V_n^2[(A_o(r_d + R_f))^2 + (\omega k A_o)^2] + V_{nf}^2 (A_o r_d)^2}{[(A_o r_d + R_f + r_d) - w^2 \tau_o k]^2 + \omega^2 (k + \tau_o r_d + \tau_o R_f + A_o C_f R_f r_d)^2} \qquad (5)$$

To compare different excess noise measurement systems prior workers proposed a ‘noise signal to noise ratio’ (NSNR) rather than the more common signal to noise ratio because, in the case of noise measurements, the signal is aperiodic and stochastic [9]. NSNR is a measure of the efficacy of the measurement system in detecting and isolating the noise resulting from the electro-optical process in the test diode from all other sources of noise and interference both originating inside the measurement system and, in the case of practical implementations, interference induced in the measurement system by the environment. In this case analysis proceeds by referring the electronics system noise to the output (denominator of (6)) then computing the noise signal at the output due to shot noise derived from 1 uA of photocurrent in the bandwidth of the measurement system for a specified diode junction capacitance (the numerator of (6)). The NSNR is the quotient of these quantities. The system noise is computed analytically by hand (5) and checked with SPICE. The system noise is heavily dominated by the noise of the TIA.

$$\frac{S}{N} = \frac{\int_a^b 2eI_{ph} |G(f)|^2 df}{\int_a^b \overline{V_{on}^2}(f) df} \qquad (6)$$

Where I_{ph} is the photocurrent, G(f) is the transfer function given by (1), V_{on} is the total noise voltage of the TIA given by (4) and a and b are the start and end of measured noise power frequency range.

Figure 4 shows the NSNR as a function of frequency for different values of C_j. NSNR is a useful metric to permit comparisons between different measurement systems independent of the bandwidth. The NSNR of this TIA is approximately 2.62 dB while C_j = 1 pF and falls to -4.624 dB at C_j = 68 pF for a 1 µA signal current. This is an significant improvement, of approximately 26 dB, over the system proposed by Lau et al. [9]. The NSNR of this TIA is -20 dB while C_j = 1 pF and the photocurrent is 10 nA.

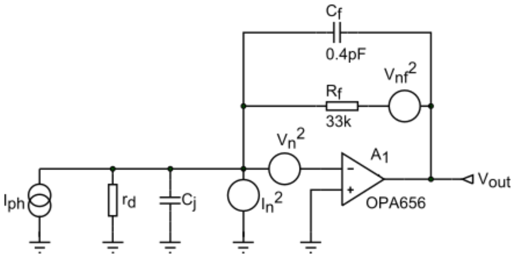

Figure 3**:** Noise model of the TIA shows feedback resistance thermal noise voltage, V_{nf} and input op-amp input current (I_n) and input voltage (V_n) noise equivalent source. I_{ph}, r_d and C_j represent the equivalent circuit of the APD.

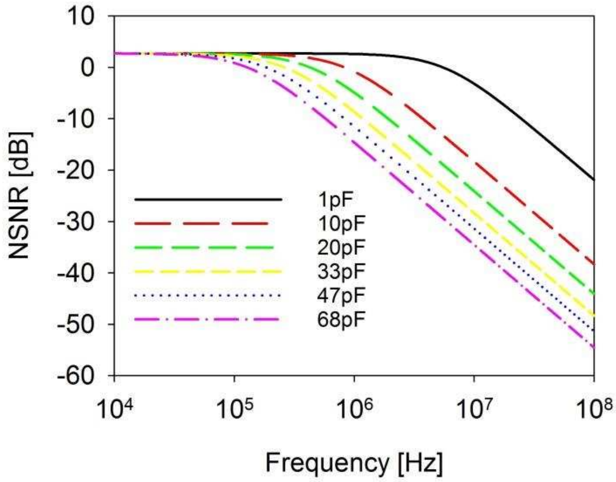

Figure 4**:** The analytical model noise to signal ratio (NSNR) against frequency with different value of the C_j from 1 pF to 68 pF for a 1 µA signal current.

2.3 Characterisation of the transimpedance amplifier frequency respose

Characterisation of the transimpedance amplifier can be accomplished by using a network analyser. An HP 4396B VNA was used in this work. The frequency response of the TIA is measured as a function of increasing APD capacitance, C_j. from 0 to 68 pF. This is shown in figure 5a. There is considerable dependence of gain on C_j at frequencies greater than 1 MHz. The value of the feedback capacitance, C_f = 0.4 pF is chosen, because it provides acceptable gain peaking over the range of values of the C_j between 0 pF and 68 pF. The response for different values of the C_j (the input junction capacitance of the APD) can be used to correct for the effects of the different gain peaking for different input junction capacitance. This allows the noise from APDs with different junction capacitance to be compared fairly.

2.4 Effective noise bandwidth (ENBW)

The effective noise bandwidth (ENBW) of the measurement system is used to correct for the different input junction capacitance of APD samples and a relationship exists between ENBW and junction capacitance of APD samples. The frequency response of the series combination of the TIA and noise bandwidth setting filter as a function of C_j is shown in figure 5b, and this data can be used to compute the ENBW of the system. Calibration results are shown in figure 6. The ENBW of the measurement system is,

$$B_{eff} = \frac{1}{G_0^2} \int_{f_1}^{f_2} |G(f)|^2 \, df \qquad (7)$$

Where G(f) is the voltage gain of the system. G_o is the gain at the centre frequency of the bandpass filter while C_j = 0 pF. f_1 and f_2 are the start and stop frequency over which there is significant voltage gain. The ENBW is calculated for different values of the C_j from 0 pF to 68 pF using (7) and this is plotted in figure 6. The ENBW can be expressed as the third order polynomial,

$$B_{eff}(C_j) = -6.3\times10^{-3} C_j^3 + 3.31\times C_j^2 + 4.61\times10^2 C_j + 92240 \qquad (8)$$

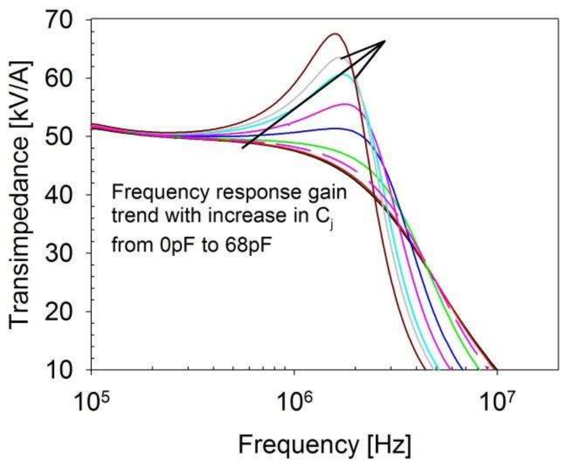

Figure 5a**:** Frequency response of TIA with input capacitance C_j from 0 pF to 68 pF.

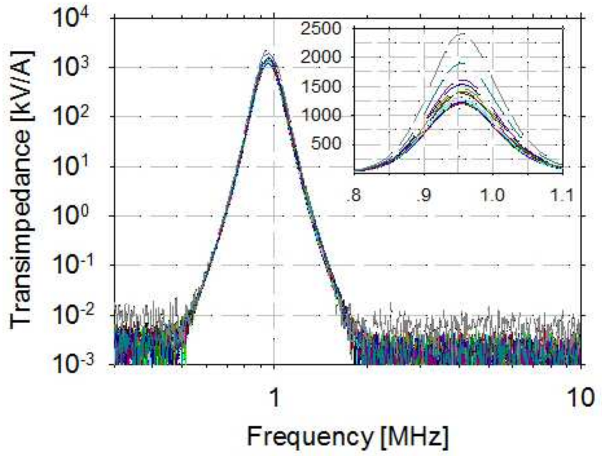

Figure 5b: Frequency response of the series combination of the TIA and noise bandwidth setting filter as a function of C_j. Lowest to highest gain; C_j = 0 pF, 1 pF, 4.7 pF, 6.8 pF, 10 pF, 22 pF, 33 pF, 47 pF, 56 pF, 68 pF, 82 pF, 100 pF, 150 pF, 220 pF.

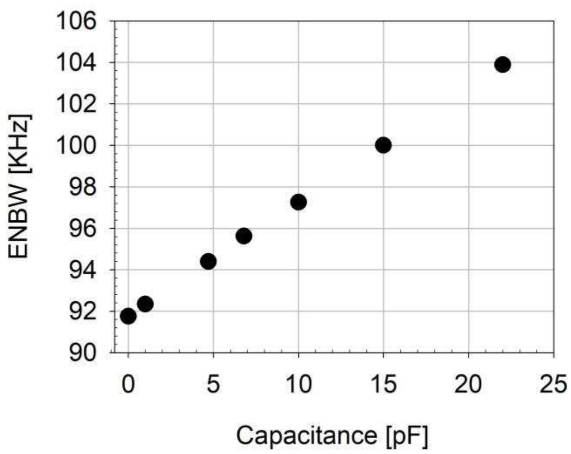

Figure 6: The effective noise bandwidth of the TIA as a function of APD junction capacitance. This plot is created by integrating the area under Figure 5b and normalizing to the centre frequency i.e. by using (6).

3 System testing

The noise measurement system is calibrated by measuring the noise power as function of photocurrent in a silicon commercial p-i-n photodiode (type BPX65) with a known junction capacitance at a fixed bias voltage before determine excess noise factor. The BPX65 has a unity gain (M = 1) so that the photodiode produces only shot noise and the excess noise factor is equal to 1. The diagram of measured noise power as function of photocurrent is shown in figure 7. The ratio of the noise power of the BPX65 to photocurrent is,

$$\frac{N_{si}}{I_{ph}} = 2eB_{eff}(C_{si})A^2 = a \tag{9}$$

The BPX65 is now replaced with the device under test (DUT). So the noise power of the DUT is,

$$N_{DUT} = 2eIB_{eff}(C_{DUT})A^2MF(M) \tag{10}$$

Where $B_{eff}(C_{DUT})$ is the effective noise bandwidth of the system when connected to the device under test, M is the corresponding multiplication and I is the multiplied photocurrent, $I = I_{ph}M$. Combining (9) and (10), the excess noise factor is,

$$F(M) = \frac{N_{DUT}}{aMI} \cdot \frac{B_{eff}(C_{si})}{B_{eff}(C_{DUT})} \tag{11}$$

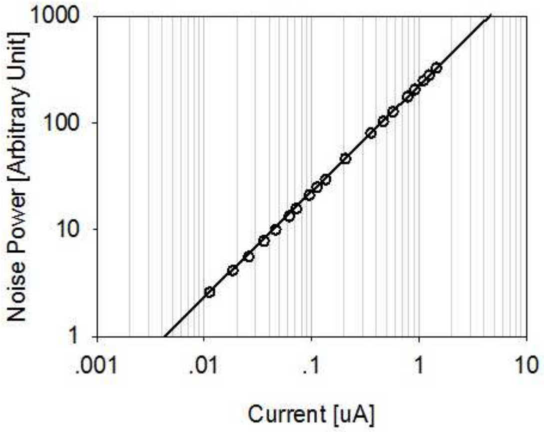

Figure 7: Noise power versus photocurrent of a silicon commercial device (BPX65).

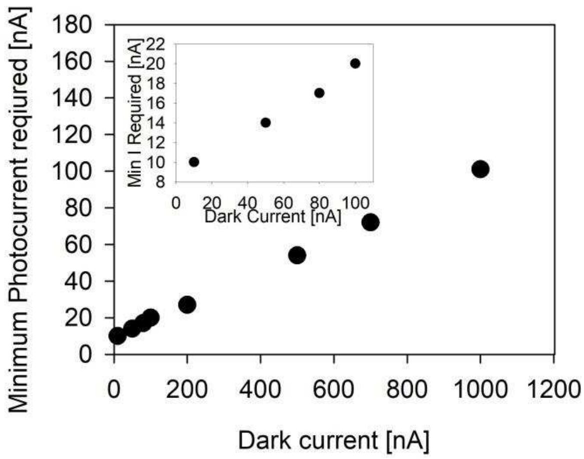

Figure 8: Minimum photocurrent required to perform the measurement in the dark current environment. The insert shows the minimum photocurrent required when the dark current is lower than 100 nA.

Figure 8 shows the measurement of the minimum photocurrent required for a BPX65 to obtain a measurable noise power using this circuit. The photo current is obtained by a modulated LED and the 'dark' current is provided by varying the illumination of the photodiode with broad band dc visible light. The noise power can be reliably measured even when the photocurrent is significantly less than the dark current. The minimum photocurrent required versus dark current has a linear relationship at higher dark current values, implying that the dark current is dominating the NSNR of the system across this range of values. The system noise however becomes relatively more significant at low photocurrents, which is why it is difficult to measure excess noise when the un-multiplied photocurrent is below 10 nA.

4 Noise measurements

The new measurement system described here has been used to measure the multiplication and excess noise factor of an AlInP APD using Thorlabs LED470L LED with a 460 nm peak emission [16]. The AlInP APD used in this work with nominal i region widths, w =1 µm, previously reported in the work of [17].

Figure 9 shows the photocurrent and multiplication of the AlInP diode using the LED. Multiplication in this diode of approximately 25 has been obtained when the primary photocurrent at 0 V was 4 nA. The excess noise versus multiplication characteristics for a AlInP diode using 460 nm LED illumination with different optical powers is shown in figure 10. The grey lines correspond to the McIntyre noise theory based on the β/α (k) ratio. The excess noise using the previous measurement system required a minimum of 0.22 µA photocurrent whereas this system now requires 10 nA as more than 22 times improvement in sensitivity. The excess noise factor of AlInP diodes with optical power attenuated by $10^{-2.3}$ and 10^{0} is similar and in good agreement with the data from the Liang et al [17] for the same width structure.

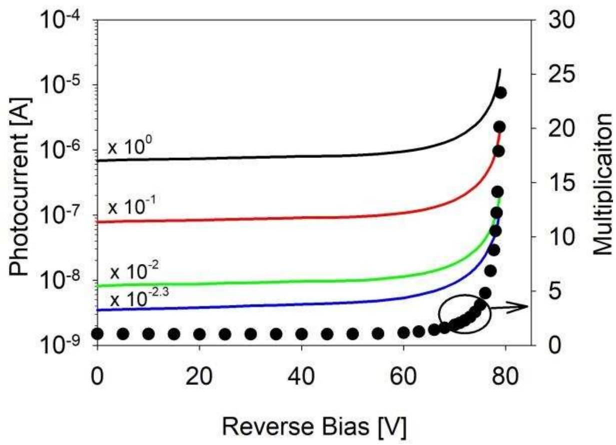

Figure 9: Measured photocurrent in AlInP diodes under 460 nm LED illumination with the optical power attenuated by 10^{0}, 10^{-1}, 10^{-2} and $10^{-2.3}$.

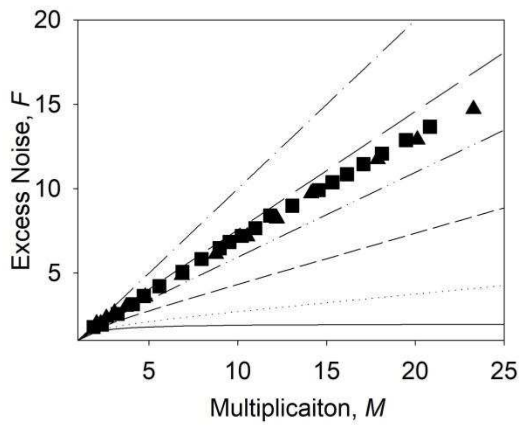

Figure 10: Experimental F versus M using 460 nm LED for AlInP diodes with optical power attenuated by $10^{-2.3}$(■) and 10^{0}(▲).

5 Conclusion

A system for measuring multiplication and excess noise in avalanche photodiodes, from lower primary photocurrents than prior work, is described and its performance analysed. The system can accurately measure the multiplication and excess noise of APDs with photocurrent as low as 10 nA. This system is at least one order of magnitude better than previous systems. The NSNR of this system is at least two orders of the magnitude higher than prior measurement systems. The excess noise factor can be measured using this system on devices with a junction capacitance up to approximately 22 pF which will cover the majority of APD detectors.

Acknowlegement

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