DESY 13-178

Overview on Low-flux Detectors

Jan Eike von Seggern

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Laboratory based searches for weakly-interacting slim particles (WISPs) of the light-shining-through-a-wall type (LSW) use visible or near-infrared (NIR) laser light. Low-noise and highly efficient detectors are necessary to improve over previous experiments. These requirements overlap with the requirements for single-photon detectors (SPDs) for quantum information (QI) experiments. In this contribution, the sensitivity of several QI SPDs is compared to photo-multiplier tubes (PMTs) and imaging charge-coupled devices (CCDs). It is found that only transition edge sensors (TESs) are viable alternatives to CCDs if the signal can be focussed to a few μm.

1 Introduction

LSW experiments search for WISPs via the process $\gamma \to \text{wisp} \to \gamma$ [1]. For a photon-counting detection scheme, the signal rate, $\dot{N}_{\text{sig}}$, is given by

$$\dot{N}_{\text{sig}} = \dot{N}_{\text{in}}\, \mathcal{P}(\gamma \to \text{wisp})\, \mathcal{P}(\text{wisp} \to \gamma)\, \eta,$$

where $\dot{N}_{\text{in}}$ is the rate of photons fed into the experiment, $\mathcal{P}(\gamma \to \text{wisp})$, η the efficiency of the detector and $\mathcal{P}(\text{wisp} \to \gamma)$ the probability for photon-WISP and WISP-photon conversion, respectively, which are both proportional to the square of the photon-WISP coupling, g. Hence, the sensitivity on the coupling, $S(g)$, i.e. the expected upper limit on g for the case that $g = 0$ is realized in Nature, scales with the detector parameters as

$$S(g) \propto (\dot{N}_{\text{ul}}/\eta)^{1/4},$$

with $\dot{N}_{\text{ul}}$ the count-rate sensitivity and η the quantum efficiency of the detector. The count rate sensitivity is typically roughly proportional to the square root of the dark count rate, $\dot{N}_{\text{ul}} \propto \sqrt{\dot{N}_{\text{dc}}}$. Hence, the sensitivity can be improved (i.e. lowered) by decreasing the dark count rate or increasing the quantum efficiency.

To compare different detectors, the figure of merit $\mu = \eta/\dot{N}_{\text{ul}}$, is used. Thus, larger values of μ identify better detectors. The count rate sensitivity is taken to be the average upper limit of unified confidence intervals and is estimated using toy Monte Carlo simulations [7].

Early LSW experiments used PMTs for photo-detection [2]. Recent LSW experiments used CCDs and lasers in the visible spectrum [3, 4]. Future LSW experiments will use NIR lasers [5] because optical elements are known to withstand high powers at these wavelengths. At NIR wavelengths, silicon based CCDs have a much reduced quantum efficiency compared to the visible spectrum. Therefore, other devices for photo-detection are sought. These detectors should have a quantum efficiency that is similar to the quantum efficiency of CCDs in the optical and a dark count rate below that of CCDs. Additionally, it is desirable that these detectors can time-resolve single photons (SPD). A review of SPDs is given in Ref. [6].

In Sections 2 to 4 (electron-multiplying) CCDs, QI SPDs from Ref. [6] and PMTs are discussed, respectively, and the figures of merit are calculated. The results are compared in Section 5. To calculate the count rate sensitivity, $\dot{N}_{\mathrm{ul}}$, a confidence level of 95 % is assumed.

2 Imaging Charge-coupled Devices

CCDs are currently the prime choice for scientific visual imaging with a wide range of devices to choose from. The imaging area of CCDs is segmented into columns each consisting of a series of MIS[1] capacitors. During data taking, these capacitors are biased into deep-depletion. Incident photons are absorbed in the semiconductor material and produce free charges which are stored by the capacitors. These charges are integrated during an exposure. At the end of an exposure, the collected charges are transported to a read-out structure and digitized. Hence, a CCD cannot resolve single photons. In addition to the charges generated by incident photons, thermally generated free charges are produced and stored as well. These constitute the dark counts, which contributes to the overall noise. The process of read-out and digitization adds a second source of noise. Hence, the total noise is given by

$$\sigma_{\mathrm{tot}}^2 = \sigma_{\mathrm{ro}}^2 + t\,R_{\mathrm{dc}},$$

where σ_{ro} is the read-out noise, t the exposure time and R_{dc} the production rate of dark counts.

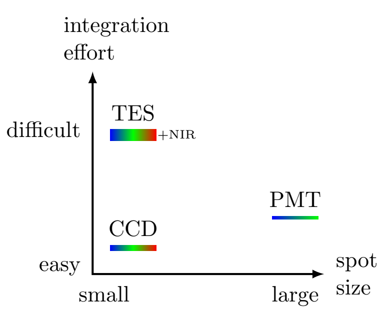

Figure 1: Schematic summary of findings. The discussed detectors are ordered by integration effort and possible spot sizes. The color scales indicate the spectral range. The colorbars' relative sizes indicate the quantum efficiency.

The LSW experiment ALPS at DESY used a commercially available, low noise CCD camera with $13 \times 13\,\mu\mathrm{m}^2$ sized pixels (PIXIS CCD) [3, 8]. A dark count rate below 8×10^{-4} e/(px s) was achieved by liquid cooling of the CCD chip and the camera was equipped with low-noise read-out electronics ($\sigma_{\mathrm{ro}} = 4.3\,\mathrm{e}$) [9]. Thus, the read-out noise is the larger contribution to the total noise for exposures shorter than 1.5 h. If the signal can be focussed to a single pixel, a data set of 20 one hour exposures yields a figure of merit $\mu = 1667$ s/photon for a quantum efficiency of 80 % which is typical in the visible spectrum.

Electron multiplying CCDs (EMCCDs) amplify the charge signal before read-out in an avalanche multiplication register [10]. This allows to neglect the read-out noise and, hence, short exposure times are possible. But at the same time, the quantum efficiency is effectively reduced by a factor of two due to the additional noise from the multiplication process [11]. The original quantum efficiency, i.e. without charge multiplication in an avalanche register, can be recovered by interpreting the read-out values in a binary fashion, i.e. photon detected yes/no [12], where a photon is counted if the digitized signal is above a threshold, $k\,\sigma$. Hence, the analysis can be reduced to that of a counting experiment. If contamination by noise and loss of signal due to the threshold can be neglected, this yields $\mu = 3307$ s/photon assuming the same values as above ($\eta = 80\,\%$, $R_{\mathrm{dc}} = 8 \times 10^{-4}$ e/(px s) and 20 h of data).

[1] metal-insulator-semiconductor structure

For NIR wavelengths, the PIXIS CCD was found to have a reduced quantum efficiency of 1.2 % [9]. The figure of merit is reduced accordingly for the PIXIS CCD ($\mu = 24\,\mathrm{s/photon}$) and EMCCD ($\mu = 50\,\mathrm{s/photon}$). InGaAs based CCDs exist, which have a much smaller band gap than silicon and, therefore, a much higher quantum efficiency ($\sim 85\,\%$) than the silicon-based PIXIS CCD. But these devices also have a dark count rate, which is six orders of magnitude above that of the PIXIS CCD [13]. Therefore, these specialized CCDs are of no help when improving the detector part of LSW experiments.

3 Quantum Information Photo-detectors

To maintain a low dark count rate and achieve a high quantum efficiency at NIR wavelengths at the same time, sensors operated at cryogenic temperatures can be used. Most of the devices listed in Ref. [6] (cryogenic or not) have however dark count rates much above that of the PIXIS CCD. Only transition edge sensors (TES) were found to have low dark count rates below that of the PIXIS CCD [14]. TES are bolometric sensors which are operated at $\mathcal{O}(50\,\mathrm{mK})$. Combined with a proper coating, high quantum efficiencies of 95 % can be reached [15]. The dark count rate and quantum efficiency expected for ALPS-II ($\eta = 75\,\%$ $\dot{N}_{\mathrm{dc}} = 10^{-5}\,\mathrm{s}^{-1}$) are assumed here as benchmark parameters [5]. The corresponding figure of merit for 20 hours of data is $\mu = 14045\,\mathrm{s/photon}$.

4 Photo-multiplier Tubes

The sensitive area of TES detectors and the pixels of a CCD are both of order $\mathcal{O}(10 \times 10\,\mu\mathrm{m}^2)$. If the signal cannot be focussed on such a small area, the pixels of a CCD can be binned. But, as discussed above, the integrated dark count rate increases at the same rate as the area of interest. Accordingly, the figure of merit and the sensitivity on the coupling may worsen significantly. In this case, PMTs are a very good alternative although they have a limited quantum efficiency ($\eta \lesssim 30\,\%$) and a limited spectral range ($300\,\mathrm{nm} \leq \lambda \leq 850\,\mathrm{nm}$) [16]. The sensitive area of a PMT consists of a photo-sensitive material with a low work function. Incident photons produce free electrons which are directed to an electron multiplier by a focussing electrode. The high gain of the electron multiplier allows single photon detection. Cooling the sensitive area reduces the dark count rate. For example, the SHIPS helioscope uses a PMT with an active area of $2.5\,\mathrm{cm}^2$, which has a peak quantum efficiency of 25 % and a dark count rate of 0.5 cnt/s when cooled to $-21°\mathrm{C}$ [18]. This corresponds to $\mu = 39\,\mathrm{s/photon}$.

Detector	η [%]	$\dot{N}_{\mathrm{dc}}$ [s^{-1}]	μ [s/photon]
CCD (visible)	80	8×10^{-4}	1667
EMCCD (visible)	80	8×10^{-4}	3307
CCD (NIR)	1.2	8×10^{-4}	24
EMCCD (NIR)	1.2	8×10^{-4}	51
TES	75	10^{-5}	14045
PMT	25	0.5	39

Table 1: Comparison of different detectors. The table lists the typical quantum efficiency, η, and dark count rate, $\dot{N}_{\mathrm{dc}}$, together with the figure of merit, μ, for silicon CCD/EMCCD, TES and PMT as discussed in the text.

5 Conclusion

Surprisingly, of all SPDs used in QI experiments, only TES detectors have a sufficiently low dark count rate to improve significantly over conventional CCDs. The figures of merit of the detectors mentioned in the above sections are summarized in Tab. 1. Of the presented alternatives, a TES is the best option. Especially in the NIR, a TES is superior to a CCD because its quantum efficiency does not deteriorate for these wavelengths. In the visible regime, CCDs remain a viable option when only few resources are available for detector development. From the values listed in Tab. 1, it seems that PMTs are the worst option. Their figure of merit is two orders of magnitude below that of CCDs (visible), which is caused mainly by their high dark count rate. However, considering their large sensitive area, PMTs are the detector of choice if the signal cannot be focussed very well. These findings are schematically summarized in Fig. 1.

Acknowledgments

The study of the PIXIS CCD was kindly supported by G. Wiedemann (Hamburger Sternwarte).

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