High-efficiency single-photon detectors

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ABSTRACT

Visible light photon counters (VLPCs) and solid-state photomultipliers (SSPMs) are high-efficiency single-photon detectors which have multi-photon counting capability. While both the VLPCs and the SSPMs have inferred internal quantum efficiencies above 93%, the actual measured values for both the detectors were in fact limited to less than 88%, attributed to in-coupling losses. We are currently improving this overall detection efficiency via a) custom anti-reflection coating the detectors and the in-coupling fibers, b) implementing a novel cryogenic design to reduce transmission losses and, c) using low-noise electronics to obtain a better signal-to-noise ratio.

Keywords: Single-photon detectors, SSPM, VLPC

1. INTRODUCTION

High-efficiency single-photon detectors are absolutely essential for optical quantum computing, scalable quantum information protocols, and fundamental physics tests. Visible light photon counters (VLPCs) and solid state photomultipliers (SSPMs) feature unique capabilities including high quantum efficiency [1, 2] and multi-photon counting capability [3]. These detectors utilize an avalanche gain mechanism; the VLPCs operate in the visible region, while the SSPMs are sensitive from the visible to beyond 10 μm (excluding a range around 1.5 μm).The VLPCs have an inferred internal quantum efficiency of 94% ± 5% (at 694 nm) [3] and SSPMs 96% ± 3% (at 660 nm) [4]. However, the actual detection efficiencies were in fact limited to less than 88% due to in-coupling losses [3, 4]. There are two main issues associated with the in-coupling optical fibers: shielding from room-temperature (RT) thermal photons, and absorption and reflection losses. We attempt to overcome these by using narrower and anti-reflection (AR) coated fibers. To reduce transmission losses to <1%, we designed a novel cryogenic setup that allows the use of shorter fibers. We thus expect a net in-coupling efficiency (at 710 nm) of > 97%. We reduced the reflection losses from the devices themselves, from ~23% to < 0.5%, by in-house custom coatings, and this technique can be applied to optimize for high-efficiency detection at any wavelength within the sensitivity range of the detectors. Finally, we discuss low-noise electronics techniques to achieve the high signal-to-noise ratio required for reliable signal detection and photon-number resolving capability. With these improvements, we anticipate actual detection efficiencies in excess of 90%.

2. DETECTOR OPERATION PRINCIPLE

2.1 Device structure

The VLPCs and SSPMs both employ similar device operation principles - both have a lightly doped arsenic gain layer and an intrinsic silicon layer (see Fig. 1). A photon absorbed in the intrinsic or the gain layer generates an electron-hole pair. When a bias voltage (~7 V) is applied across the device, the hole accelerates towards the gain layer and impact ionizes an impurity atom, thus initiating an avalanche event. Since the impurities require only ~50 meV to be ionized, the devices must be cryogenically cooled to ~6K in order to prevent thermal excitations of these atoms. In order to facilitate the different operational wavelength ranges, the device structures of the two detectors are slightly different; VLPCs have a slightly modified structure to suppress the sensitivity to infra-red photons. Both devices have low multiplication noise (because only one carrier causes an avalanche), thereby facilitating photon-number resolution.

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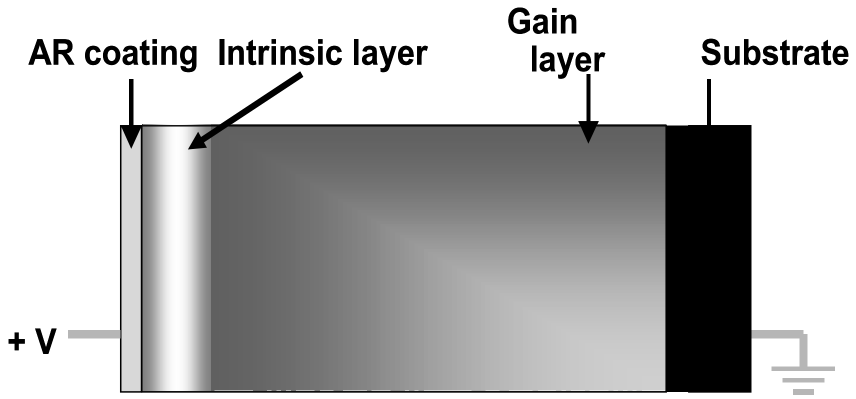
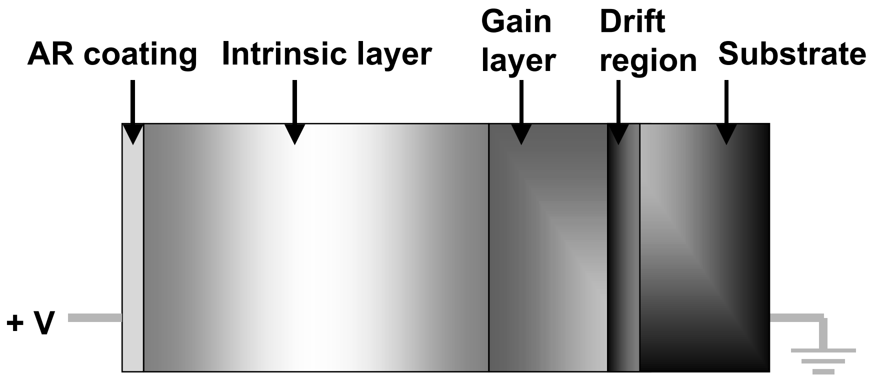
Moreover, the avalanches are localized to a filament that is typically much smaller (~4 μm) than the device area (~ 1mm^2).



a.



b.

Fig. 1a. Device structure of a Solid-State Photo Multiplier. 1b. Device structure of a Visible Light Photon Counter.

3. LOSS IN OPTICAL FIBERS

There are two main issues associated with the in-coupling optical fibers: background and loss. Because of their IR sensitivity, the VLPCs and SSPMs require shielding from room-temperature (RT) thermal photons. For this purpose, we use plastic (PMMA) fibers, which have very high attenuation above ~750 nm. However, if they are warm, the fibers themselves will emit thermal radiation, so at least part of the fiber (closest to the detector) must be cooled. The contribution from the blackbody radiation of the fibers can be further minimized by using narrower fibers, which necessarily have a smaller surface area. We are currently testing three fiber diameters: 0.5, 0.75 and 1 mm (the detectors have a surface area of ~1mm^2). Additionally, the optical fibers have undesirable absorption and reflection losses at the detection wavelengths. Typical loss due to Fresnel reflections at each fiber interface is 4%. AR coatings for the fibers in principle have to be optimized at each end because one end is at 300 K and the other at 6 K. We have custom-coated our fibers, measuring < 1% reflection at 710 nm at both temperatures. The typical attenuation at 710 nm for PMMA fibers is 0.9 dB/m. Our first setup, shown in Figure 2, consists of a dual-neck Dewar. Helium is filled through one neck and light is coupled onto the detectors via optical fibers through the other. This setup requires ~20-cm long fibers, which corresponds to a transmission loss of ~4%. To overcome this loss, we have designed a novel cryogenic setup (Fig. 3) that requires shorter fibers and should reduce the transmission loss to < 1% while still retaining excellent filtering of the IR photons (transmission is <~40% per mm for wavelengths >1 μm). In this setup, the detectors are glued onto the copper sample holder of an optical constant-flow cryostat using a cryogenic thermal adhesive[1]. Light is directly coupled in using optical fibers through one of the windows. With this modified setup, we expect a net in-coupling efficiency (at 710 nm) of > 97%. Further, our tests also indicate that the fibers are insensitive to thermal cycling (without aging), which was previously thought to be an issue [2]. However, thermal cycling the fibers and the fiber assembly over a larger period of time could still be a problem.

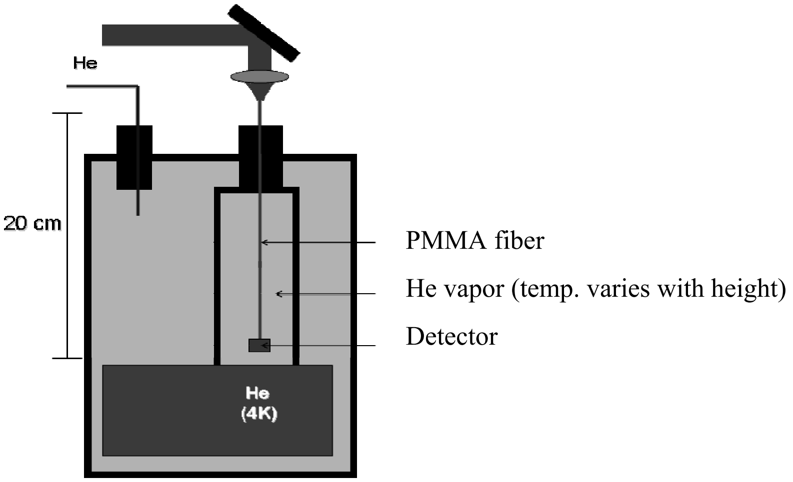


Fig. 2. Schematic of our first cryogenic setup, using a dual-neck Dewar. Helium is filled via one input and light is coupled in to the detectors through the other.

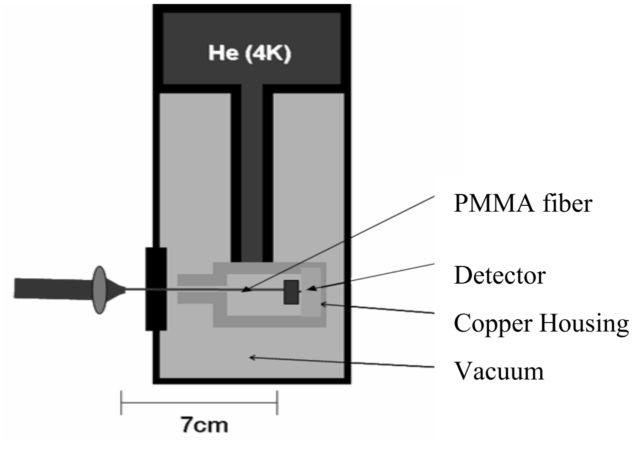


Fig. 3. Our modified cryogenic setup. The detectors are attached to the sample holder of an optical constant flow cryostat using cryogenic thermal glue. Optical fibers couple the incoming light through one of the cryostat windows.

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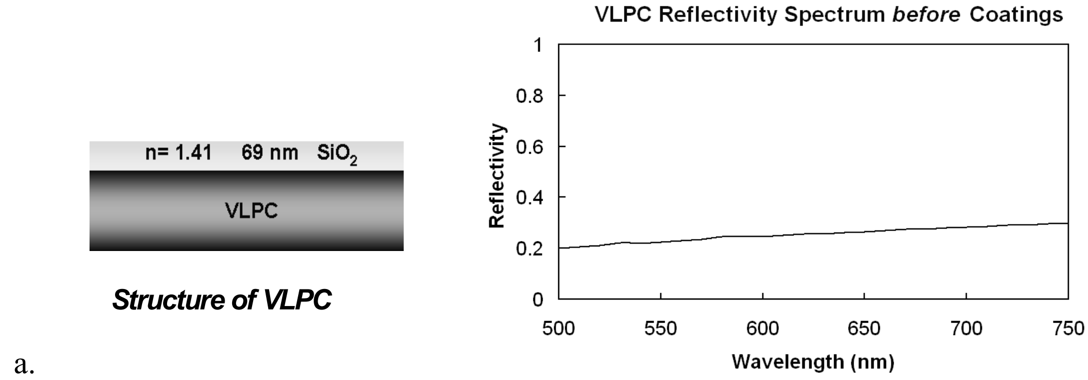
[1] In the modified setup the sample is in vacuum and hence cooling occurs solely through conduction via the thermal adhesive. Hence, cooling to 6K in this setup was a challenge, which was solved by clamping down the detectors (to increase the area of contact) and by reducing the heat load though the wires. Vapor cooling occurs in the dual-neck system and hence this is not an issue in the first setup.

4. DETECTOR AR COATINGS

Due to the high refractive index of silicon, the Fresnel reflection at the detector surface is about 30%. High reflectivity spherical refocusing mirrors have been used to mitigate this issue [2], but losses due to secondary reflection at the detector surface can still be quite high. Thus, AR-coating the detectors is essential. However, optimal coating of the detectors for one's wavelength of choice is not always an option during fabrication. Therefore, the capability to modify the coatings for different wavelengths is necessary. Our VLPCs, supplied by Dr. A. Bross of Fermilab, came with a 69-nm layer of SiO_2, resulting in ~23% reflection at 710 nm. Figure 4a shows the structure and the measured reflectivity spectrum of the VLPCs prior to any in-house coatings.

We custom-coated our VLPCs, using in-house fabrication facilities, to optimize the detector performance at 710 nm. Since removing the existing SiO_2 layer might damage the detector, we chose to add a multilayer AR coating on top of the 69-nm SiO_2 layer. An additional 250 nm of SiO_2 followed by 89 nm of SiN resulted in $< 0.5\%$ total reflection at 710 nm [Fig. 4b]. Using such techniques, both the SSPMs and VLPCs can be optimized for high-efficiency single-photon detection at any wavelength within the sensitivity range of the detectors.



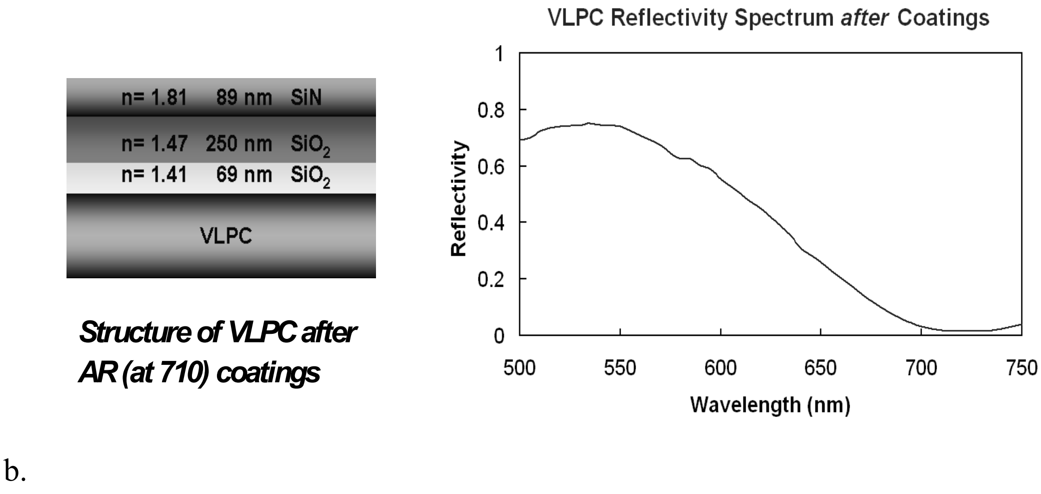


Fig.4a. Structure and measured reflectivity spectrum of the supplied VLPCs. n is the refractive index of the layer.
b. Structure and measured reflectivity spectrum of VLPCs after applying custom AR-coatings optimized for 710 nm.

5. LOW NOISE ELECTRONICS

Reliable signal detection and photon-number resolving capabilities require a high signal-to-noise ratio and, hence, low-noise electronics. We have tested several low-noise (noise factor: ~1.2 dB) room-temperature amplifiers including the Miteq Au-1464 , Mini Circuits ZPUL-30P and the Miteq Au-1525 . The latter was found to be the most suitable for our application, with a gain of ~65 dB and a noise figure of ~1 dB . The noise with this system can be further reduced, but at the cost of decreasing the measurement bandwidth. Hence, we are also working on a cryogenic preamplifier to enhance the signal before it travels through lossy cables. The cryogenic amplifier has a gain ~6 dB. To test the operation of the detectors, we use a short pulse width (~3 ns) 100 KHz red LED source [5].

6. EXPECTED CHARACTERISTICS

The overall detection efficiency has been measured to be ~85% for the SSPMs [4] and ~88% for the VLPCs [3]. However, the intrinsic efficiency for both detectors is expected to be > 92%. Both detectors saturate around 10 million counts per second and have dark counts ~7 kHz. The response time is ~1 ps, but the total transport time is ~ 5 ns [3, 4]; Further, both detectors should display photon-number resolving capabilities (where the n-photon detection efficiency scales as ξ^n) [7].

7. CONCLUSION

High detection efficiency in single-photon counters would enable a number of exciting experiments, including the first loophole-free test of the Bell's inequality [6], and scaling towards the practical implementation of optical quantum computing protocols. With their extremely high internal quantum efficiency, VLPCs and SSPMs are ideally suited for this purpose. We have demonstrated that the coupling losses can be reduced significantly by AR-coating both the detectors and optical fibers for the operating wavelength. We are currently designing better electronics and testing other methods to reduce the losses in the fibers. With these improvements, we anticipate actual detection efficiencies in excess of 90%.

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