

Moon Photonics High Sensitivity HgCdTe APD Detectors for Lidar, FSO and Quantum Optical Applications

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ABSTRACT

Moon Photonics is a start-up spun-off from CEA/Leti to create a commercial offer of high sensitivity IR detectors with high temporal resolution at IR wavelengths taking benefit from the exceptional performance of their HgCdTe APD technology. The first product series, presently available for sampling, will address applications in which the system integration competes with performance. This High Operating Temperature (HOT) Series is available in two version for Lidar and FSO with sensitivities a factor 8 to 50 times higher than commercially available InGaAs-InP APD-receivers, while expanding the spectral range up to 2.5 μm . The second QUANTUM-series detectors will, in particular, address the requirements in quantum optical application, with performance level at the state of the art while being operated at high temperature in a small size-low power package that is compatible with industrial scaling and space born applications.

Keywords: High sensitivity, Infra-red, APD, Lidar, FSO, quantum photonics, HgCdTe

1. INTRODUCTION

HgCdTe APDs are promising for a large range of photon-starved applications due their exceptionally high gain, in excess of 100 [1], low multiplication noise corresponding to an excess noise factor below $F=1.3$ and spectral sensitivity extending into the mid Infra-Red (IR) range. These characteristics has enabled ground breaking applications demonstrations in applications ranging from low flux astronomical imagery to high data rate free space optical (FSO) communications. Until present, the commercial offer of such detectors has however been limited to focal plane arrays for astronomy from Leonardo UK [2] that need to be operated at low operating temperatures, below $T=100$ K, and there are no solutions available to address applications in need of high temporal resolution and sensitivity, in particular at wavelengths exceeding the InGaAs detection range above 1.6 μm .

FSO and Lidar applications are driven by compromises in terms of system performance, such as the range, with the size, weight, power and cost (SWAPc) of the terminals. In this case, the detector sensitivity is a main driver for system optimization. In the field quantum optical applications, such as Quantum Key Distribution (QKD), computing and sensing, great progress has been made in recent years through the deployment of high single photon detection efficiency (PDE) super conduction nanowire single photon detectors (SNSPDs)[3, 4]. However, due to their ultra-low temperatures, below 3 K, their industrial scaling and their use in space are expected to be limited by the detector SWaPc.

This communication presents the technology and products that are or will be commercialized by Moon Photonics. Moon Photonics was spun-off from CEA-Leti in January 2026 to create a commercial offer of high sensitivity detectors for time resolved applications such as Lidar, FSO and quantum optics. The detectors are based on the HgCdTe APD detector technology developed CEA/Leti during the last decades, combining high performance APDs, with gains up to 1000 at bandwidths up to 2GHz, with additional features that increases the detector sensitivity and facilitate the system integration of the detectors through increased optical area, guaranteed EO-performance and reduced EMI sensitivity. The APD technology and the additional features, corresponding to flip-chip hybridization of each APD onto in-house designed resistive feed-back transimpedance amplifiers (RTIAs) and monolithically integrated micro-lenses, are described in section 2. The detectors will be commercialized in hermetic packages adapted for the different use cases. For applications requiring small form factor detectors, such as Lidar and FSO, the so-called HOT series detectors will be integrated in small TO packages and operated at a controlled temperature using thermo electric cooling (TEC). The characteristics of these detectors are reported in section 3. At lower operating temperature of the APDs, the detectors are capable of down to

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single photon detection and responds to the requirements in the quantum optical and deep space FSO applications. These applications will be addressed by the QUANTUM-series detectors that will be integrated into cryo-coolers to be operated at temperatures in the range of $T=80-100$ K. The maturity of the technology and the expected characteristics of the QUANTUM-series detectors are presented in section 4. The final section 5 presents a summary of the first generation of Moon Photonics detectors and discuss the perspectives for the next generations of detectors.

2. DETECTOR TECHNOLOGY

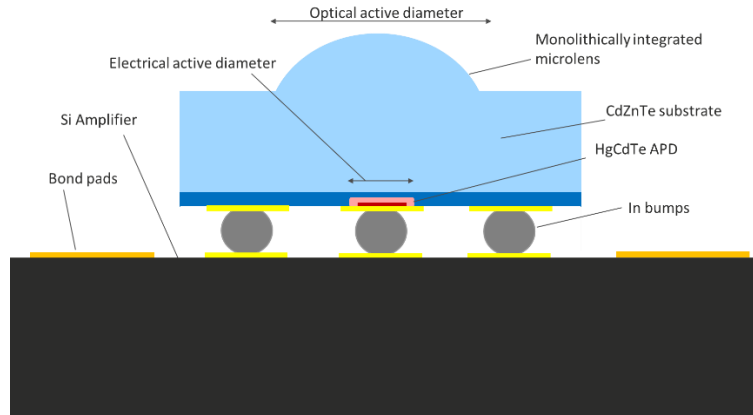


Figure 1. Schematic illustration of Moon-Photonics detector technology with high avalanche gain HgCdTe APD hybridized on a specifically designed Si-CMOS amplifier and equipped with a monolithically integrated micro-lens.

Moon Photonics record high sensitivity photodetectors are integrating three main functional blocks; high avalanche gain HgCdTe APDs, hybridized low noise Si-CMOS amplifiers and monolithically integrated micro-lenses, illustrated in Fig. 1. These blocks are all contributing in obtaining unprecedented sensitivity for IR detection with high temporal resolution and paving the way for simplified and/or enhanced photonics as will be detailed in the following sub-sections. The detectors are implemented in a planar back-side illuminated geometry which is mandatory for the hybridization and the formation of micro-lenses in the transparent CdZnTe (CZT) substrate used for growing the HgCdTe detector layers. This geometry is also in favor of the formation of detector arrays, like 4 quadrant detectors that were developed for combined beam tracking and signal detection [5].

HgCdTe APD technology

The HgCdTe avalanche photodiodes (APDs) have been optimized to produce unmatched gain values that can reach values in excess of 1000, while conserving a low multiplication noise, characterized by an excess noise factor in the range of $F=1.2$ to $F=1.3$, fast response times, approaching 2 GHz, and being tolerant to space application through a high tolerance to proton irradiation [6]. At Moon Photonics, the APD architecture and technology have been developed at CEA/Leti with the goal to obtain a high gain and high bandwidth while preserving an optically active area [7].

The choice of HgCdTe APDs does not only allow achieving a close to ideal avalanche multiplication, it also allows to adjust the band-gap to detect infra-red light at wavelengths up to $10\text{ }\mu\text{m}$ [1]. For the first generation of detectors from Moon Photonics, the APDs have been optimized for the detection of wavelengths up to $2.5\text{ }\mu\text{m}$. This allows to extend the use of eye-safe laser beyond $1.6\text{ }\mu\text{m}$ with the benefit of increased gas sensing capacity, more photons per Joule and higher stealth in defense applications. The latter being due to the lack of low cost-highly sensitive imagers at these wavelengths. The cut-on wavelengths for the detectors depends on the back-end process of the assembled detectors. In presence of a residual CdZnTe substrate used to form the micro-lenses, the cut-on is $\lambda_{on}=850\text{ nm}$. In case of a complete substrate removal, the detectors are capable of detecting light through the visible spectra down to deep ultraviolet [8].

The sensitivity of a APD based photo-detectors depends on the amplifier noise, v_{amp} , the APD gain and the noise generated by the APD, v_{APD} . The APD gain can be increased as long as v_{APD} , which is mainly due to dark current generation in the APD, is lower than v_{amp} [7]. There are multiple possible contributions to the dark current noise from the APD, such as an amplified diffusion current, tunnel currents from the multiplication layer or leakage currents in the passivation layer. At high temperatures, the dark noise is limited by the diffusion current and the maximum useful gain and sensitivity of the detector depends directly on the operating temperature of the APD. The typical variation of the equivalent input dark

current density (NEI) of the first generation of Moon Photonics APDs is plotted in Fig. 2 as a function of operating temperature for an APD with electrical diameter of 40 μm . The associated maximum gain for a transimpedance amplifier (TIA) with an input noise of $i_{\text{TIA}}=1 \text{ pA}/\sqrt{\text{Hz}}$ ranges between $M=4$, at $T=300 \text{ K}$, to $M=200$, at $T=200 \text{ K}$. The HgCdTe APD technology has been optimized to reach the highest gain at the highest BW for application that require to operate the APDs at high operating temperature. Fig. 3 reports typical gain curves and impulse response measured as a function of the reverse bias of the APDs, displaying avalanche gain values in the range of $M=100$ to 200, associated with bandwidths of 1 to 2 GHz in APDs with diameters ranging between 30 and 40 μm . The high temperature APD technology have also been validated for APD diameters ranging between 20 to 80 μm in which the dark noise increases at constant operating temperature and the BW tends to be reduced with increasing diameter.

The gain values can be compared with the typical maximum useful gain $M=10$ in standard InGaAs APDs with an InP multiplication layer [9,10], limited mainly by a strong increase in the excess noise at higher gains. A more stable operation at higher gains have been reported for InGaAs APD with Sb based multiplication layers in which useful gains in excess of $M=100$ at relatively low excess noise factor of $F=3.5$ and low dark currents have been demonstrated [11,12]. It can be expected that such APD should enable improved detector sensitivity except if amplifier integration, high excess noise or gain instabilities limits the system performance.

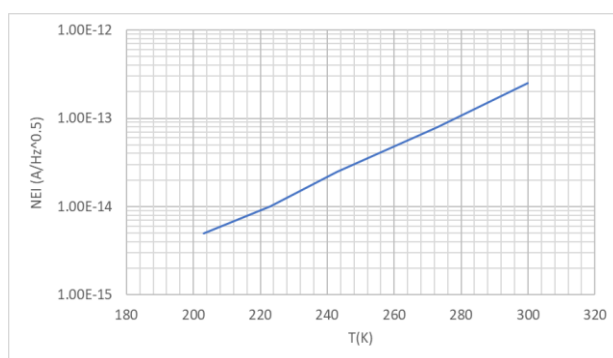


Figure 2. Typical evolution of the Noise Equivalent Input current density (NEI) at $M>100$ as a function of operating temperature of a 40 μm HgCdTe APD from Moon Photonics and CEA/Leti.

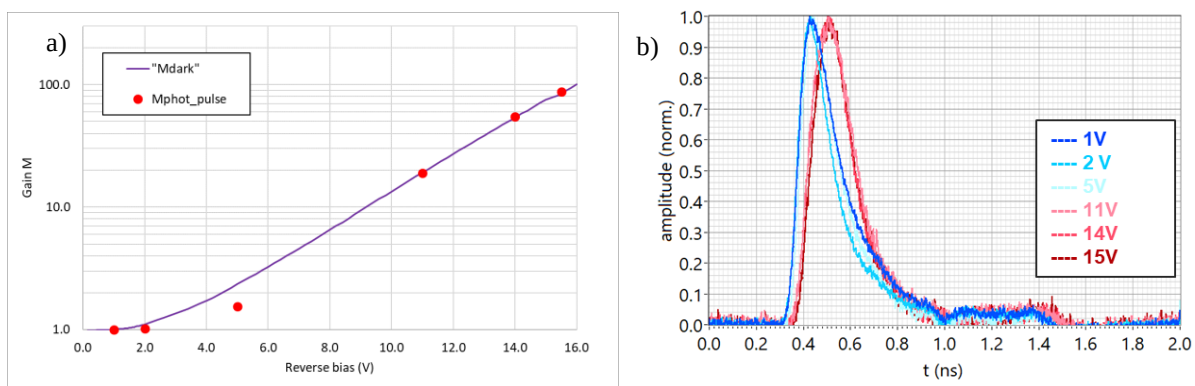


Figure 3. a) Dark current gain (continuous line) and integral impulse response gain of a HgCdTe APD at $T=300\text{K}$ and b) normalized impulse response time measured at $T=300 \text{ K}$ in a 30 μm diameter HgCdTe APD. The fall time of the response time corresponds to a BW of 1.4 GHz.

At lower temperatures the dark current is limited by carrier generation in the multiplication layer and the amplifier noise can be reduced due to the reduced thermal fluctuation in the amplifier. The latter enables to detect the signals produced by single photons at the condition that the APD gain exceed the standard deviation of the amplifier noise. Under these conditions, the detectors can be used for quantum optical applications in which the dark noise of the APD will be detected as false detection of photons contributing to the so-called dark count rate (DCR) in the photon counting detectors. To achieve the highest photon detection efficiency (PDE) it is required to maximize the APD gain without altering the temporal resolution or generating an excess of dark count rate. The APDs used for these applications have been subject to a specific optimization resulting in a constant impulse response of the detector, corresponding to a bandwidth of 1 GHz, up to a

multiplication gain in excess of $M=1000$. The corresponding variation of the APD gain as a function of reverse bias is illustrated in Fig. 4a). The dark current of this APD was measured at zero thermal flux using a deported capacitive feedback transimpedance (CTIA) amplifier that was developed at CEA/Leti for high dynamic range Lidar measurement [13]. Fig. 4 b) reports the dark current as a function of reverse bias at different operating. It can be seen that the dark current is below the experimental limitation of about 1 fA up to a reverse bias of 15 V, corresponding to an APD gain of 200. At 16.5 V, the dark current is below 10 fA at $M=400$ at an operating temperature up to $T=90$ K. The corresponding gain normalized current corresponds to a DCR=156 Hz. This level of DCR is compatible with most single-photon-based quantum optical applications. The PDE that can be achieved with this level of gain depends on the level of amplifier noise and will be further discussed in section 3.

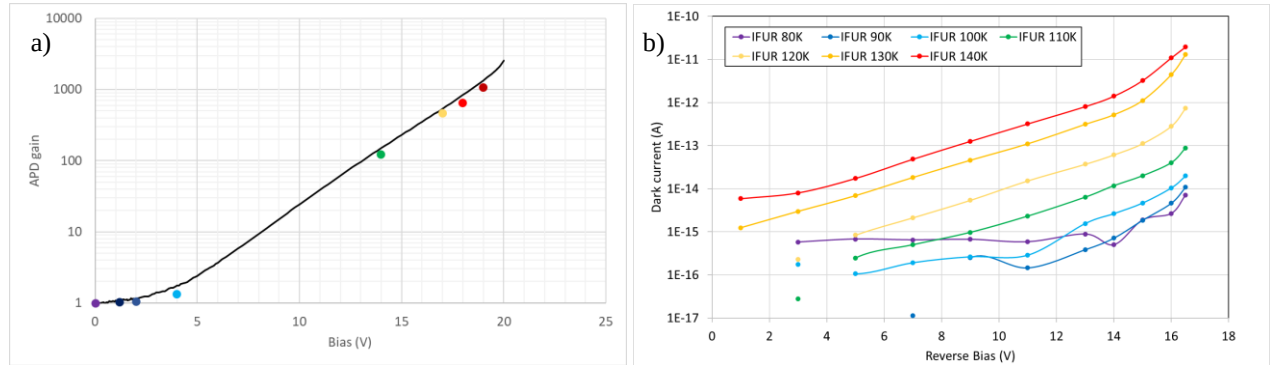


Figure 4. a) Dark current gain (continuous line) and integral impulse response gain of a HgCdTe APD at $T=300$ K and b) dark current as a function of reverse bias measured on a 30 μ m diameter HgCdTe APD between $T=80$ K and $T=140$ K .

Hybridized amplifier solutions

The use of a hybridized amplifier to transfer and amplify the charge generated in the photo-diode are common in focal plane array application but are rarely used in single element time resolved application. The use of a hybridized amplifier brings additional value to photo-detectors through a reduced amplifier noise, due to the reduced input capacitance, reduced sensitivity to electromagnetic interference (EMI), through the suppression of a bond-wire between the APD and the amplifier, and a guaranteed performance through complete electro-optic characterization of the performance of each APD-amplifier die.

Moon Photonics have developed three different Si CMOS resistive feedback trans impedance amplifiers (RTIAs) to respond to the specific requirement in Lidar, FSO and quantum photonics in collaboration with CEA/Leti. The amplifiers have been conceived based on the heritage from the development of read-out integrated circuits (ROIC) for focal plane array applications and dedicated development of amplifiers for time resolved applications for single photon detection [5,14,15] and Lidar [13].

The Lidar and FSO amplifier have been developed specifically for Moon Photonics and are expected to come back from foundry end of august 2026. The amplifier for quantum optical application was conceived within the scope of the high-risk project “LUMIERE” and is expected to be coming out from foundry and be tested in 2027. The expected characteristics of the amplifiers are resumed in Table 1.

The Lidar amplifier have been conceived to be operated close to room temperature with a bandwidth of 200 MHz. The transimpedance gain have been selected to conserved a high dynamic range while minimizing the output noise. Single ended output was chosen for this amplifier with the objective to reduce the power consumption and to achieve a linear dynamic range of 1000 between the amplifier noise and the highest output level with linear response. The input noise $i_{TIA}=300$ fA/ $\sqrt{\text{Hz}}$ is about 10 times lower than the one in commercial deported TIAs with comparable bandwidth, like AD8015 in which $i_{TIA}=3$ p A/ $\sqrt{\text{Hz}}$. This shows on the capacity shows on the capacity of the hybridized amplifier solution to reduce the amplifier noise and increase the sensitivity even before using the avalanche gain. The level of noise is low enough to enable single photon detection at avalanche gains in excess of 100. However, such use of this amplifier requires the use of APDs with a low enough dark current and the noise level is expected to be too high to reach PDE values in excess of 90 % even at low operating temperatures.

The amplifier conceived for FSO applications has a larger bandwidth and a lower dynamic range. The limited bandwidth, $\text{BW}=1.3$ GHz, is due to limitations in the Si-CMOS technology used for the design in the present version of the amplifier.

The reduced bandwidth will lead to a limitation in sensitivity when used in FSO applications at data rates of 2.5 Gbps of about 1 dB as will be detailed in section 3. The noise reduction compared to a deported amplifier solution was found to be less remarkable than for the Lidar amplifier, although a reduction of a small factor 2 is expected compared to the best deported amplifiers that is combined with the lower EMI sensitivity, guaranteed detector performance and being adapted to the polarity of our APDs. The high noise is once again due to bandwidth limitations in the Si-CMOS technology which is why we aim to design a new amplifier with higher bandwidth and lower noise for the next generation of detectors.

The amplifier for quantum photonic applications has been optimized for operation at $T=80$ K and slightly lower APD capacitance. This has allowed to achieve a strongly reduced noise compared to the Lidar amplifier at a similar bandwidth of about 200 MHz, which will allow to detect events at a rate up to 250 MHz. This low level of noise will enable high PDE values even at relatively low avalanche gain values. The development of amplifier using another transistor technology, such as Si-Ge biCMOS, is expected to enable an increase of the bandwidth to values above 1 GHz and to achieve count rates in excess of 1 GHz while preserving the same level of noise and a corresponding high PDE.

Table 1. Specifications of the RTIA amplifiers developed for Moon Photonics detectors.

Amplifier (typical application)	Lidar	FSO	Quantum	
Parameter	typical	typical	typical	Units
T op	0	0	-193	°C
Bandwidth	0.2	1.3	0.28	GHz
Gain - 50 Ohm charge	150	9	450	kOhm
Input current noise density	0.3	2	0.1	pA/√Hz
Input noise - rms	71	172	22	electrons
Dynamic range	>1000	500	0.8	μm
Output (50 Ohm)	Single	Differential	Differential	N.A.
Power consumption	50	100	100	mW

Monolithically integrated Micro-lens technology

The use of micro-lenses allows to increase the optically active area while preserving a low APD capacitance, low dark noise and high bandwidth. The backside illumination geometry and the use of a transparent CZT substrate during growth of the active HgCdTe layers allows to form lenses directly into the substrate. The geometry of the lenses is intrinsically limited by the size of each detector die and by the initially thickness of the substrate to less than 1 mm. The lenses can be used to concentrate a convergent beam onto the APD or to image the field of view (FOV) onto the electrically active area by placing the lens at its focal distance. The latter is illustrated in Fig 5 a). In this case, the radius of curvature of the lens is adapted to the focal distance needed to generate an optical spot within the electrical active diameter of the APD. The corresponding spot diameter of the APD is given as a function of the FOV for different focal lengths in Fig. 5 b). It can be seen that a spot compatible with an APD diameter of 40 μm can be achieved with FOVs between 22° to 42° for focal distances of $f=300$ μm and $f=150$ μm, respectively. The optical active diameter depends on the radius of curvature and our present control of the lens formation process to values slightly in excess of the focal distance. For example, an optical active diameter larger than a focal length of $f=150$ μm is compatible with a FOV=42° and an APD diameter of 40 μm. Larger optical areas, up to 500 μm, can be achieved with smaller FOV and larger focal length.

At present, we are in the process of selecting lens design for the future standard products as a function of our first clients' requirements. The development of custom application specific designs will possible in the future, depending on the market opportunities and social impact of the applications.

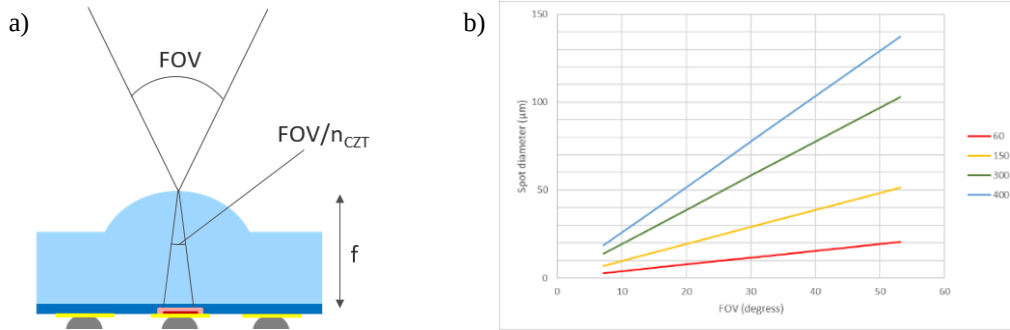


Figure 5. a) Schematic illustration of the optical coupling through a CdZnTe micro-lens with the incoming light focused on the top side of the lens and b) Variation of the spot size for different FOV of the collecting optics and focal distances varying between $f=60$ to $400\ \mu\text{m}$.

3. HOT-SERIES DETECTORS FOR LIDAR AND FSO

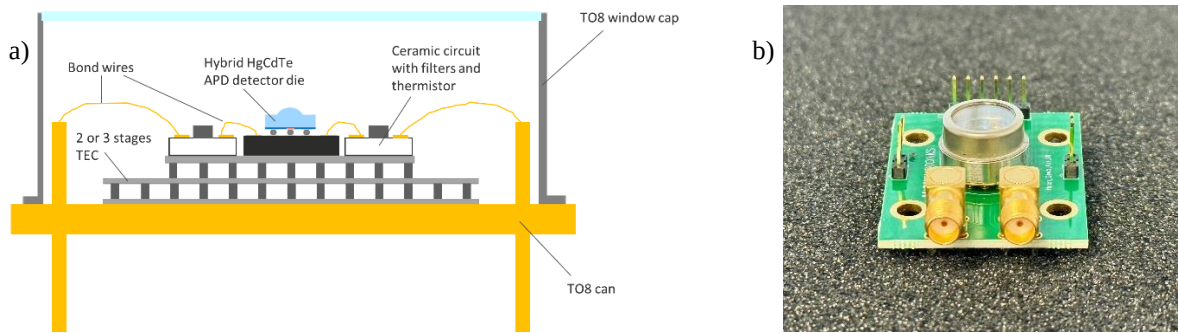


Figure 6. a) Schematic illustration of a packaged Moon Photonics HOT series detector with a 2 stage TEC and b) a HOT-series detector module with the demo-kit proximity PCB.

The first generation of the HOT-series detectors will be distributed as fully packaged detector modules using commercial TO8 cans. The packaged detector will integrate the following elements, illustrated in Fig 6 a):

- A 2 or 3 stage thermo-electric cooler (TEC) element to control the operating temperature of the APDs.
- A ceramic circuit to connect and filter the bias supply to the amplifier and the APD.
- The detector dies with a HgCdTe APD equipped with a micro-lens and hybridized onto an application specific amplifier.

The package will be hermetically sealed with a commercial window cap with a high transmittance through the NIR to SWIR spectral ranges.

In the first sales, the package detector can be delivered with a demo-kit, illustrated in Fig. 6 b), to simplify the electrical and thermo mechanical interfaces of the detector and speed up the tests of the detectors.

Two products are presently being commercialized for higher and lower bandwidth applications using the FSO and Lidar Si-CMOS amplifiers, respectively. The corresponding preliminary data sheets are reported in Table 2. The choice of standard designs of the micro-lenses are not yet fixed and will eventually depend on client requirements. It can be seen that the expected sensitivity is strongly dependent on the operating temperature of the APD. This shows that the higher sensitivity comes at the cost of a lower operating temperature and, as a consequence, a higher thermal dissipation due to the use of higher TEC currents. This cost is expected to be largely compensated in systems by the increased sensitivity compared to other packaged detector solutions based on commercial deposited amplifiers and standard InGaAs APDs, ranging between $200\ \text{fA}/\sqrt{\text{Hz}}$ to $1200\ \text{fA}/\sqrt{\text{Hz}}$ [9,10]. The corresponding gain in sensitivity with Moon Photonics solutions ranges from a factor 8 to 50. A direct comparison with higher gain Sb-based InGaAs APD [11] is difficult as these detectors

are distributed as bare dies and that the sensitivity of a received to also depend on the choice of the TIA, the influence of the dark and high excess noise at high gain and the signal integrity when coupled to a deported TIA. The data reported in reference [11] showed on a dark current limited sensitivity of 22 to 46 fA/ $\sqrt{\text{Hz}}$ for APDs with active diameters ranging from 30 to 200 μm . This limits the possible gain in sensitivity to a factor 4 to 8. It should however be reminded that these values were obtained at high gain values, in excess of $M=100$ at which the excess noise value is increasingly high, $F>3.5$, which will strongly impact the information that can be extracted from the detected light and increase the noise from detected stray light. This makes it difficult to predict the sensitivity of receivers made with such APDs, in addition to the fact that it will depend on the choice and implementation of a deported TIA. The difficulty to predict the performance in these detectors due to such causes is illustrated by the results reported in [12] in which a lower-than-expected sensitivity was measured during bit error rate tests (BERT) at 2.5 Gbps, corresponding to a sensitivity that was 3 to 4 dB lower than the predictions.

The highest sensitivity of the H200M Lidar detector corresponds to RMS noise level of 1 photon and do as a consequence allow detecting light pulses of a few photons with high SNR and detection efficiency. At present, the sensitivity is still limited by the dark noise of the APD and a reduction of the dark current in the next generation of APDs is a main objective at Moon Photonics to reach such performance at a higher operating temperature.

As mentioned in the previous section the bandwidth of the FSO amplifier is at present limited to $\text{BW}=1.3 \text{ GHz}$ and will impact the sensitivity for the reception of 2.5 Gbps data. The impact of the limited bandwidth has been simulated for 2.5 Gbps NRZ data, taking into account the photon shot noise, the excess noise factor of the APD $F=1.25$ and a measured impulse response of the APD with a $\text{BW}=1.6 \text{ GHz}$ and a $\text{QE}=80\%$. The total noise of the amplifier was supposed to be at 2.1 electrons rms, which corresponds to the high sensitivity limit of the H1G detector at the lower operating temperature range. The impact on the receiver sensitivity at a $\text{BER}=10^{-3}$ is reported in Fig. 7. It can be seen that a sensitivity below 20 ppb is obtained for a TIA BW in excess of 1.4 GHz. At 1.3 GHz and 1 GHz, the sensitivity penalty ranges between 1.1 dB (22 ppb) to 4.1 dB (44 ppb). It is however important to note that even with this limitation, the expected level of sensitivity has not yet been reported for direct detection of NRZ data at 2.5 Gbps and is therefore expected to strongly enhance and simplify the implementation of FSO terminal. In addition, a further increased sensitivity will be achieved in the next generation of Moon Photonics FSO detectors, though the development of a higher bandwidth-lower noise amplifier and APDs with reduced dark current.

Table 2. Moon Photonics first generation HOT series detector data-sheet.

Detector type (typical application)	H1G (FSO)	H200M (Lidar...)	
Parameter	typical	typical	Units
Active diameter	50-200	50-400	μm
Field of view	28	28	degrees
System bandwidth ($f_{-3\text{dB}}$)	1.3	0.2	GHz
Quantum efficiency ⁽¹⁾	>80	>80	%
Spectral cut-on	0.85	0.85	μm
Spectral cut-off	2.5	2.5	μm
Responsivity at $M=100$ ⁽²⁾	900	15 000	kV/W
Excess noise factor F	1.3	1.3	NA
Noise equivalent power NEP ⁽³⁾	25 ⁽⁴⁾ to 60 ⁽⁵⁾	5 ⁽⁶⁾ to 25 ⁽⁷⁾	fW/ $\sqrt{\text{Hz}}$
Dynamic range	>1000	>1000	NA
Output	Diff.	Single	NA

1: at the peak of AR coating

2: 50 Ohm charge for $\lambda=1.55 \mu\text{m}$

3 : at $\lambda=1.55 \mu\text{m}$

4: at -30°C , dark current and gain limited

5: at 0°C , dark current limited

6 : at -70°C , dark current limited

7: at -30°C , dark current limited

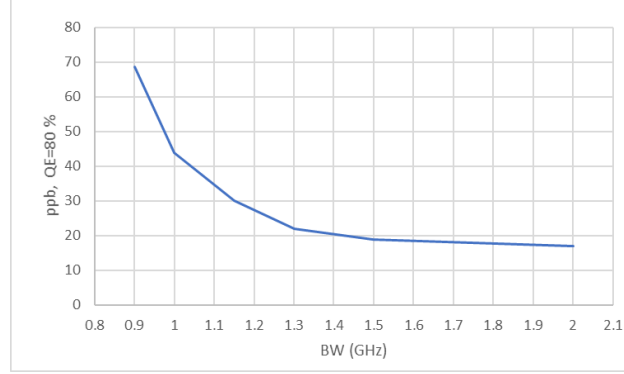


Figure 7. Expected variation of the receiver sensitivity for 2.5 Gbps NRZ data at $BER=10^{-3}$, supposing an APD with a $QE=80\%$, $F=1.25$ and gain normalized amplifier noise of 2.1 electrons. The highest sensitivity, at 2 GHz BW, corresponds to an optical average power of -52.7 dBm (17 ppb).

4. QUANTUM-SERIES DETECTORS FOR QUANTUM OPTICAL APPLICATIONS AND DEEP-SPACE FSO

The high avalanche gain in HgCdTe APDs, reaching values of 1000 while conserving a fast response time, and the use of low noise TIAs, as described in section 2, allows to achieve linear mode single photo detection with the following advantage compared to SNSPDs and Geiger mode APD detectors, commonly referred to as SPADs :

- Absence of a recovery time allow to detect signals at a rate limited by the BW of the APD or the amplifier that will enable GHz count rates without gating and on a single detector.
- Information conservation of the number of photons detected within each event on each detector element. The capacity to perform photon number resolved (PNR) detection is limited by the quantum efficiency of the detector, that introduces a loss, and the excess noise of the avalanche diode, that disperse the amplitudes for each detected photon leading to overlapping distributions for the amplitudes of different detector photon numbers. Nevertheless, a calibration of the excess noise and the QE do allow an estimation the photon number distribution through a repetitive detection of a well-prepared quantum state of light.

In addition, the low dark current demonstrated at high gain values shows that high PDE values in excess of 90 % can be reached with the present HgCdTe APD technology at low DCR, close to 100 Hz, when using a low noise amplifier and being operated at a relatively high operating temperature (80 K) compared to SNSPDs, that are operated below $T=2.5$ K. The expected high PDE value have been estimated from our most recent measurements with high gain APD hybridized onto the CL110 amplifier with a relatively high noise [15]. The measured internal false negative rate (1-PDE) at an APD gain $M=470$ at different threshold level of false positive events on the amplifier noise are compared in Fig. 8 a) to the analytical expression for the cumulated probability distribution of a gaussian distributed amplifier noise and single photon signal, estimated using a χ^2 distribution with $F=1.28$, normalized by the average APD gain M . Details of the measurement method can be found in reference [15]. It can be seen that there is a good agreement between the measured and calculated values agree. This allows to estimate the expected performance using an amplifier with lower noise. Such estimation has been made in Fig 8 b) for an amplifier noise of 30 electrons rms, which slightly higher than the one expected for our new amplifier dedicated to quantum optical applications. At a false positive rate of 10^{-6} , which allows to reach an amplifier induced DCR of 100 Hz at a detection rate of 100 MHz, the expected internal PDE=95 % which is comparable to the highest values reported for SNSPDs.

This shows on the capacity of to respond to requirements of quantum photonics while being operated at an operating temperature compatible with high thermal dissipation on the cold post, that opens the perspective of large channel counts per cryostat and/or space application such as QKD, through the strong reduction in size, weight and power consumption (SWaP) of the detectors. The latter is also key to the industrial scaling of all applications that requires down to single photon detection.

The first detector modules for quantum photonics or deep space channel will be available in 2028, pending the foundry of the new amplifier, an optimization of the APD jitter, a reduction of the amplifier glow, the photo emission in Si transistors

that limits the DCR to MHz values in the present detectors, and the development of dedicated package to operate the detectors at 80 K with an optimal optical coupling. The expected characteristics for this first generation of detectors are reported in Table 3. This detector will be available as a single channel detector and as a multi-channel detector through the integration of multiple detectors in the same cryostat.

The objective for the following generation of Quantum detectors is to achieve higher count rate and lower jitter through the development of a higher bandwidth amplifier using another transistor technology.

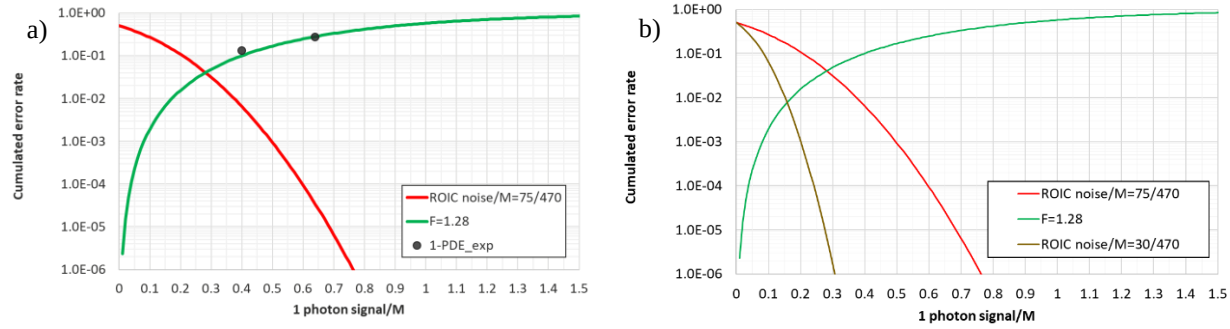


Figure 8. a) Analytical probability distributions of the amplifier noise of 75 electrons rms and the single photon avalanche gain amplitude with $F=1.28$, normalized by the average gain $M=470$ compared to the measured internal false negative probabilities at two different thresholds and b) the same distributions compared to an amplifier with a noise of 30 electrons rms, leading to a high detection efficiency of 95 % even at a false positive rate of 10^{-6} .

Table 3. Data sheets for the first and second generation of Moon Photonics Quantum series detectors.

Detector type	Q200M ^(a)	Q1G ^(b)	
Parameter	typical	typical	Units
Optical coupling	SMF	SMF	NA
System bandwidth (f_{-3dB})	0.2	1	GHz
Photon count rate	0.25	1.25	GHz
Photon detection efficiency PDE ⁽¹⁾	>90	>99	%
Dark count rate DCR	100	10	Hz
timing jitter	<100	<50	ps
Spectral cut-on	0.8	0.8	μm
Spectral cut-off	>2.2	>2.2	μm
Dynamic range	1 to 100	1 to 100	Photons
Power consumption ⁽²⁾	20	20	W

a: samples available in 2028

b: samples available in 2029

1: at $\lambda=1.55 \mu\text{m}$

2: cooling and control electronics

5. SUMMARY AND PERSPECTIVES

The start-up Moon Photonics are commercializing high sensitivity IR photo-detectors to enhance and/or simplify time resolved photonic applications such as Lidar, FSO and quantum photonics. The photo-detectors are based on technologies that have been developed over the last decade at CEA/Leti in response to the increasing number of applications that requires to detect small quantities of light with high temporal resolution over the IR spectral range. In particular, the detector integrates HgCdTe APDs that have been optimized to achieve record high avalanche gain at high bandwidths while preserving a low dark current and excess avalanche noise. Additional value to the detectors is added by the use of specifically designed amplifiers that are hybridized with the APD, allowing to reduce the amplifier noise, the sensitivity to EMI and a performance guarantee through the direct measurement of the system performance of each detector die. In addition, each detector is equipped with a monolithically integrated micro-lens that increases the active optical diameter while maintaining a low dark current noise and high BW of the APDs.

Moon Photonics will commercialize two series of detectors, the HOT and QUANTUM series. The HOT-series has been developed to address application with strong SWaP requirement, such as Lidar and FSO, is presently available for sampling. These detectors are integrated in compact TO type packages with two amplifiers with bandwidths of 200 MHz and 1.3 GHz that allows addressing high dynamic range Lidar measurement and FSO reception at data rates up to 2.5

Gbps. These modules are 8 to 50 times more sensitive than existing commercial InGaAs-InP APD receivers with TIAs that will, in combination with a spectral range extended up to 2.5 μm , enhance the capacity and/or simplify high end photonic systems.

The QUANTUM series will be commercialized in 2028 following the engineering of a compact low power packaging with optimized optical coupling. These detectors bring a low SWaP detector solution, at the performance level of the reference SNSPD detectors, for quantum photonics and deep space FSO and enables industrial scaling and space deployment of such applications.

The development of next generations of detectors will be pursued within a common laboratory with CEA/Leti, with the objectives to optimize the APD technology, the hybridized amplifiers and the optical coupling to respond to requirements of existing and new applications. The optimization activities will address the APD performances in terms of gain, bandwidth and dark current, with a long-term goal to reach 10 GHz bandwidths. In parallel, the goal is to extend the application capabilities of the detectors by forming small format arrays and expanding the spectral range towards the mid IR range.

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