Single photon sensor for Mid-Infrared Lidar (SMIL)

Art Branny[1], S. Steinhauer[1], Monique Gevers[2], Niels Noordzij[2], Nima Kalhor[2], Niels Los[2], Sander Dorenbos[2], Andreas Fognini[2], and Val Zwiller[1*]

[1] KTH Royal Institute of Technology, Department of Applied Physics, 106 91 Stockholm, Sweden
[2] Single Quantum BV, Lorentzweg 1, 2628 CJ Delft, Netherlands
*Corresponding author: zwiller@kth.se

ABSTRACT

Our mission is to secure clean air for everyone everywhere. To pursue this aspiration, we pioneer the use of quantum technologies for atmospheric monitoring. Our new single photon sensors advanced mid-IR technology beyond its current boundaries in terms of sensitivity and signal quality. Using our mid-IR detector, we demonstrated CO_2 remote gas detection at the single photon level, taking a step towards a lidar system able to provide 3D real-time data on air quality for an entire city.

Keywords: single photon; lidar; mid-IR, superconducting nanowire detector, gas detection.

1. INTRODUCTION

Atmospheric pollution is a global societal issue. Today, 91% of the world's population breathes unhealthy air (WHO), due to high concentrations of airborne pollutants which can be particles, droplets, or gases. Urban air is the most polluted and varied, in which pollutant concentrations often exhibit localized and short-lived maxima. This hyperlocal and temporal nature of urban air leads to highly personalized exposures and the biggest health impacts. This presents the need for remote and continuous monitoring in three-dimensions (3D) and in real-time that would fully quantify the composition and nature of polluted urban air. However, there is no sensor currently capable of undertaking this task due to the insufficient detection efficiency, spatial and temporal resolution of currently available mid-IR photodetectors.

To address this challenge, we propose to combine the state-of-the-art superconducting nanowire single photon detectors (SNSPD) with lidar technology. This presents a unique opportunity for employing SNSPD in gas sensing lidar and realizing its full potential. Owing to single photon sensitivity, high temporal resolution and near-IR operation, this new technology holds promise to create a disruptive shift by turning lidar into a live 3D air-quality imager. This will go beyond current spatially and temporally fragmented data of ground-based local monitoring stations and space borne satellites by providing live, high-resolution data.

To tackle this challenge, we developed and fabricated a commercially graded mid-IR SNSPD in SMIL. The detector operates across a wide spectral range between 1330 nm and 2050 nm that overlaps with the absorption bands of several important gas species such as CO_2, CH_4 and NO. We highlight that our detector achieves single photon sensitivity across this entire range and still maintains high signal to noise ratio equal to 10^4. Specially, at 2 microns, such performance already supersedes currently established mid-IR technology based on semiconducting HgCdTe avalanche photodiodes (MCT APDs). We also integrated our detector into a table-top lidar prototype and performed a successful CO_2 gas sensing experiment using only 8 pW input laser power. Our sensitive detector relaxes stringent requirements of high-power mid-IR lasers and enables photon-starved outdoor sensing applications that inherently suffers from high losses.

2. STATE OF THE ART

Data on atmospheric composition in cities is fragmented and fails to capture the dynamics of urban air and its impact on human health. Spaceborne satellites and ground monitoring stations measurements inherently suffer from spatial and temporal gaps. In contrary, lidar has been shown to be capable of imaging airborne pollutants and gases in 3D, in real time and with high selectivity. Although promising, lidar technology still falls short of addressing the challenge due to the lack of a high-performance mid-IR photodetector.

Infrared detection is enabled by technologies based on semiconductors, superconductors, and frequency converters. Today, MCT and APDs show the best performance and are being deployed in NASA missions (i.e. ASCENDS, OCO-2). These devices reach 90% quantum efficiency across the 0.4 - 4.3 µm spectral range. They, however, show overwhelmingly large background noise at 0.1 Mcps, which leads to an extremely low signal-to-noise-ratio (~10). They are also far from reaching single photon sensitivity. In lidar, these shortcomings cause significant compromise between time-depth resolution trade-off, preventing real-time 3D imaging and impose the use of hardly available high-power mid-IR lasers which is still an active field of research.

Commonly used Si and InGaAs APDs can detect single photons but suffer from a sharp cut-off around 1 µm (1.7 µm), making them unsuitable for mid-IR applications. Similarly, photomultiplier tubes with InGaAs photocathodes can only detect single photons up to 1.6 µm.

In recent years, research efforts have led to the development of commercially available SNSPDs which superseded their predecessors in overall performance for near-IR wavelengths up to 1.5 µm. These improvements enabled further ranging, high sensitivity, high depth resolution, and fast detection in several remote sensing applications. However, SNSPDs operating beyond the near-IR still require further work that impedes the progress on remote gas sensing.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

SNSPD technology has never been employed in gas sensing applications, its synergy with lidar could lead to a disruptive technological shift - turning lidar into a live 3D gas and pollutant imager. Single photon lidar challenges the current status quo of unsatisfactory data quality on outdoor air pollution, recognised worldwide to be the biggest threat to human health.

The SMIL project took the first step towards a long-term goal of creating an infrastructure of environmental gas and pollutant imagers in urban areas. While our research focuses on detecting CO_2, we laid the groundwork for the full air coverage by developing a ready-to-use apparatus and methodology (TRL 1-3) which can be expanded to other gas molecules and particulate matter.

The new generation of mid-IR SNSPDs developed in our project advanced 2 µm detection beyond the state of the art set by MCT APDs: infrared detection technology gained 3 orders of magnitude in signal to noise ratio due to a reduced intrinsic noise floor from 100 k to 10 counts per second. SNSPDs also brought the sensitivity of mid-IR detection down to the physical limit of detecting single photon events which constitutes of another 3 order of magnitude improvement. The single-photon detection limit of our SNSPDs also removed the requirement for high-power mid-IR light sources.

The next step of the SMIL project is to translate the overall high performance of SNSPDs into advancing sensing lidar capabilities in terms of ranging, sensitivity, and spatial resolution. This goal would have been demonstrated in phase 1 if it wasn’t for the COVID-19 lockdown. Nevertheless, we anticipate 3 times longer detection range and an order of magnitude improvement in timing and depth resolution than is currently possible, paving the way to an urban air-quality imager.

The breakthrough character of our project is not only manifested in significant advancement of mid-IR technology and its implication in lidar but also in the underlying aspiration. Our approach is to provide high quality data to enable data driven initiatives towards resilient, sustainable, and liveable cities.

The breakthrough character of advancing mid-IR detection with SNSPDs stems from its enabling capability to subsequently advance many other disciplines including environmental science, chemistry, medicine, and industry, leading to far-ranging impact.

4. PROJECT RESULTS

The overall detector performance and therefore its application is determined by the quality of the superconducting film, the detector’s design (i.e. film thickness, type of substrate) and the nanofabrication process. One of the major results of the SMIL project is the successful fabrication of SNSPD optimised for mid-IR operation through the development of new nanofabrication processes.

Optical characterisation

The detector operates across a wide spectral range from 1310 nm to 2050 nm. Table 1 lists system detection efficiency (SDE) for several wavelengths within the range. The operating range covers multiple absorption bands of CO_2, NO, CH_4 and NH_3 making the detector well-suited for gas sensing applications.

λ (nm)	1310	1550	1580	1625	1692	1855	2051
SDE	40 %	73 %	55 %	63 %	36 %	29 %	10 %

Tab. 1. System detection efficiency.

Large noise levels are among the main challenges in mid-IR detection as they significantly reduce the signal to noise ratio. Fig. 1 shows typical signal to noise comparison present in our detector for 3 wavelengths. The noise levels in our detector are kept low enough to reach signal to noise ratios above 10^4, achieved at a bias current equal to 6 µA. In addition to an outstanding signal to noise ratio, the detector shows single photon sensitivity across the entire spectral range, enabling gas sensing measurements at the single photon level.

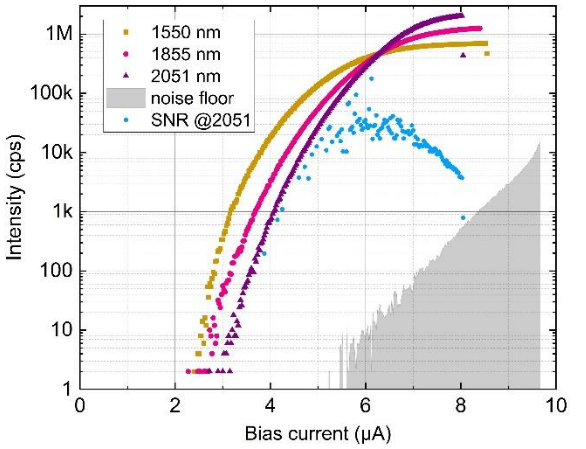

Fig. 1. Signal to noise comparison for three operating wavelengths - 1550 nm, 1855 nm, and 2051 nm.

Gas sensing with single photon lidar

Our table-top gas sensing lidar sensor consists of the mid-IR SNSPD characterised above, a low power, narrow linewidth, tuneable laser, and a multi-pass Herriott gas cell. The Herriot cell increased the optical path length 26 times to reach a total length of 6.8 m within a 26 cm cell. The cell transmission of 0.4 emerges from multiple and imperfect reflections from gold and silver mirrors. After including fibre coupling and transmission, the total transmission of the optical system (excl. the detector) becomes 0.11 (0.03) for 1572 nm (2051 nm). Because of our outstanding single photon detection sensitivity, these losses do not hinder gas sensing experiments.

To perform the experiment, the cell was filled with 100% CO_2 at 0.78 mbar pressure and kept at room temperature. The detector biased at 6 µA recorded the laser intensity while the laser wavelength scanned ±0.5 nm around R16 CO_2 absorption line at 1572.335 nm (6359.967 cm^{-1}). The raw data in fig. 2a reveals three lines superimposed on a periodic background. The periodic modulation is fitted and subtracted from the raw data as it arises from the interference produced by interfaces of the cell windows. The concentration of CO_2 per unit length is obtained by calculating the transmission $T = I_{ON}/I_{OFF}$ and the optical density OD = -log(T), where I_{ON} is the attenuated intensity and I_{OFF} is the background intensity, as displayed in fig. 2 b,c, We measure OD = 0.6. The background intensity (I_{OFF}) of 200 kcps, corresponds to the average energy of 25 fW (10^{-15} W), still 10^4 times larger than the noise level. Such high sensitivity and signal quality remove stringent requirements for mid-IR high-power laser sources.

Our results provide the proof of concept that merging SNSPD and lidar technologies brings advantages to remote gas sensing. The next step towards realising a 3D gas imager is to perform range-resolved experiments using a pulsed laser. There, the sub-100 ps timing resolution of our detector offers high depth resolutions.

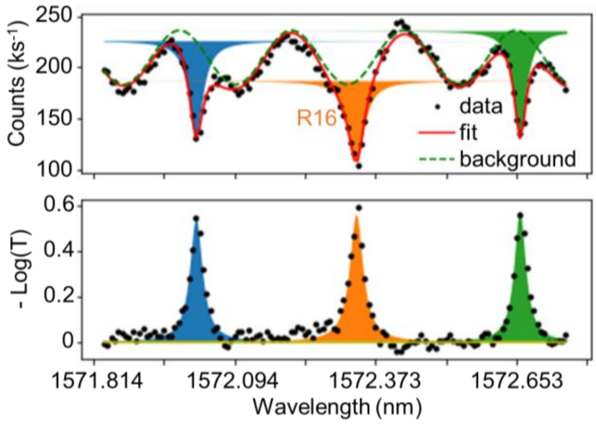

Fig. 2. Remote sensing of CO_2 with SNSPD using scanning absorption spectroscopy.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Scaling up our technology is relatively straightforward as Single Quantum has the ability to industrially produce the detectors developed in SMIL. Minimal Valuable Product 1 (MVP 1). Mid-IR SNSPDs. Partner: Single Quantum is self-sufficient

We envision the development of complete lidar systems for CO_2 and then expand to other gases (NO_x, SO_2, CH_4) and airborne polluting particles (PM2.5, PM 10). We identify several possible partners with relevant and complementary expertise to develop a complete atmospheric sensing system.

We also have taken first contact with European based SME manufacturer of outdoor lidar systems, as well as a University group leading research on environmental monitoring from Ecole Polytechnique in Paris who is keen to take our detector and plug it into their lidar system. The group works on the CH_4 space lidar mission MERLIN which will be launched in 2024 and the HOLDOn european project on implementation of the new MCT APD in atmospheric measurements.

We are in contact with the Swedish environmental agency and national air quality reference laboratory (SLB-Analys, IVL, ACES department of SU in Sweden)

5.2. Project Synergies and Outreach

We have identified several Attract phase 1 projects with clear links to our project that could combine force to develop a strong industrial effort:

- POLMOSSA on mid-IR high power short pulse laser

- HyPeR on remote detection of marine plastics

On time tagging electronics

- FastICpix - Integrated signal processing for a new generation of active hybrid single photon sensors with ps time resolution
- LIROC, Novative RadHard front-end ASIC for LIDAR
- Next generation of time to digital converters (NXGTDC)

5.3. Technology application and demonstration cases

- *Climate, Health, demographic change and wellbeing;*

With high fidelity sensing tools at hand, one can start investigating interactions in a realistic pollutant mixture to discover techniques capable of cleaning our polluted air. Live, 3D images of atmospheric pollution covering a whole metropolitan area would be a powerful tool to monitor and enforce environmental regulation.

- *Secure, clean and efficient energy;*

Our system will also enable leak surveillance at industrial sites as well as optimisation of combustion processes and help towards the goal of reducing industrial exhaust.

5.4. Technology commercialization

Single Quantum has a solid and successful track record in bringing scientific innovation to the market and has the engineering expertise to develop these results in an industrial produce.

5.5. Envisioned risks

We identify no major technological risks. Because support for the development of these technologies in China is very strong, we foresee a risk that European efforts will lack behind both industrially and scientifically.

5.6. Liaison with Student Teams and Socio-Economic Study

We will involve students in the project at various levels: a PhD student and 3 master students would form an adequate team to develop a synergy with teaching efforts and increase European competitiveness in this emerging field.

For the socioeconomic study, we would try our best to supply students with the information needed to evaluate the societal impact of our work.

6. ACKNOWLEDGEMENT

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

7. REFERENCES

[1] Brown, S.L. & Eisenhardt, K.M., 1998, Competing on the Edge: Strategy as Structured Chaos, Harvard Business School Press, Boston, MA, USA. (Book style)

[2] Gavetti, G., 1999, Cognition, capabilities and corporate strategy making, Working paper, The Wharton School (Working paper or unpublished manuscript style)

[3] Prahalad, C.K. & Bettis, R.A., 1986. The dominant logic: a new linkage between diversity and performance, Strategic Management Journal, 7(6): pp. 485-501. (Journal style)

[4] Romero, D. & Molina, A., 2015, A multidisciplinary framework and toolkit to innovate customer-centric new product development, 2015 IEEE International Conference on Engineering, Technology and Innovation/ International Technology Management Conference (ICE/ITMC), Belfast, 2015, pp. 1-10. (Conference Proceedings style)

[5] Teece, D.J., 1988, Technological change and the nature of the firm. In Technical Change and Economic Theory, Dosi, G., Freeman, C., Nelson, R., Silverberg, G. & Soete, L. (eds.). Pinter Publisher: London, UK, pp. 256-281. (Edited book style for chapter)