Lewis Fleming, Sam Ahmadzadeh, Jonathan Pomfret, Ewan Waddell, Greg McGann, David Hutson, Emma Keel, Matthias Kauer, Matthieu Bellanger, Ian Brinkley, and Des Gibson "Light powered battery-less non-dispersive infrared sensor for methane gas detection", Proc. SPIE 12999, Optical Sensing and Detection VIII, 129990L (20 June 2024); https://doi.org/10.1117/12.3022146

Light Powered Battery-less Non-Dispersive Infrared Sensor for Methane Gas Detection

Lewis Fleming*[a,b], Sam Ahmadzadeh[a,b], Jonathan Pomfret[a,d], Ewan Waddell[b], Greg McGann[a], David Hutson[b], Emma Keel[a], Matthias Kauer[c], Matthieu Bellanger[c], Ian Brinkley[b], Des Gibson[a,b]
[a]The University of the West of Scotland, Paisley, Scotland, UK, PA1 2BE;
[b]Albasense Ltd, Paisley, Scotland, UK, PA1 2BE;
[c]Lightricity Ltd, The Oxford Science Park, Oxford, OX4 4GB
[d]G&H PLC, Dowlish Ford, Ilminster, TA19 OPF, UK

ABSTRACT

Methane is a significant contributor to global warming so reducing methane emissions, particularly from oil and gas operations, is among the most cost effective, impactful actions governments can take to achieve climate goals. Preventing methane leakage impacts economic productivity and worker safety too. Large-site leak detection requires reliable cost-effective distributed sensors.

Methane leakage is also an issue for several other industries. However, hard wiring is not practical or cost effective and battery power is unacceptable due to the need for regular changes requiring engineers working in hazardous areas at great expense. The sustainability challenge of additional travel associated with device maintenance and disposal of used batteries in the millions is also environmentally unacceptable. Worker safety monitoring with lower-cost portable methane detectors requires bulky, rechargeable battery-powered devices that the industry is seeking to avoid for operational and environmental reasons. Various low-cost sensor technologies have been applied to methane sensing (catalytic, optical - non-dispersive infrared (NDIR), semiconducting metal oxide and electrochemical) with catalytic/pellistor sensors formerly being dominant but in recent years replaced by NDIR sensors overcoming issues of accuracy, susceptibility to poisoning, short lifetimes, power consumption, recalibration and requirement for oxygen presence. It also has the advantage of being a fail-to-safe technology.

In this work, we present an optical NDIR gas sensor that uses a fast-response semiconductor light source/detector optopair operating at <1 mW power consumption, compatible with powering from photovoltaic based energy harvesting. This is a step change from current state-of-the-art gas sensor technologies and orders of magnitude lower than filament/thermopile based detectors. Fabrication of the sensor is discussed, including; semiconductor mid-IR optopair fabrication, mid-IR optical interference filter deposition and injection molded 2-mirror parabolic reflector optical system preparation. Sensor response to methane is discussed and light harvesting operation is demonstrated, enabling compatibility with wireless distributed methane sensor networks.

Keywords: NDIR sensing, methane, oil and gas, wireless network, environment

1. INTRODUCTION

Methane is a significant contributor to global warming with 86x the warming power of CO_2 over the first 20 years after reaching the atmosphere [1]. Reducing methane emissions from oil and gas operations is among the most cost effective, impactful actions governments can take to achieve climate goals. Preventing methane leakage impacts economic productivity and worker safety too [2]. Large-site leak detection requires reliable cost-effective distributed sensors. Methane is also produced in agriculture, landfill waste, mining, refineries, petrochemicals and biogas production. The scale of the challenge is illustrated in the USA where fugitive emissions from oil and gas total 13m tons/year, $2bn in lost revenue (globally $30bn). There are approximately 1m active wells around the U.S. requiring ongoing monitoring, 300,000 miles of interstate gas pipelines, thousands of compressor stations and over 100 liquefied natural gas facilities. A 2020 study estimated 630,000 leaks in U.S. distribution. Current approaches to measuring methane leaks at facilities are periodic remote sensing surveys with laser-based optical solutions costing £100k+. Distributed methane sensor networks would improve measurement regularity and granularity but hard wiring is not practical or cost effective and battery power is unacceptable due to the need for regular changes requiring certified engineers working in hazardous areas at great expense, the sustainability challenge of additional travel and disposal of used batteries in the millions. Worker safety monitoring with lower cost portable methane detectors requires bulky, rechargeable battery-powered devices that the industry is seeking to avoid for operational and environmental reasons.

In this work, we demonstrate the world's first self-powered, battery-free, long-range wireless methane sensor nodes for industrial leak detection. Albasense Ltd have demonstrated gas sensor technology feasibility with IV-VI based fast response semiconductor light source/detector optopairs demonstrating ability to make much lower cost and lower power consumption methane sensors. At <50 μW (with 10 μW targeted) these are already a step-change reduction from the most advanced III-V LED-based solutions and orders of magnitude lower than common tungsten filament-thermopile NDIR methane sensors, bringing it within range of light energy harvesting.

Lightricity photovoltaic (PV) technology [3] is established in manufacturing and has already been applied to powering various LoRa (Long Range) and BLE (Bluetooth Low Energy) IoT sensor devices including ultra-low power NDIR CO_2 gas sensors (a world first). It is the world's most efficient and smallest commercially available indoor PV technology, 6x more power-per-unit area at 200 lux than state-of-the-art amorphous silicon and outdoor performance comparable to the best available PV technologies making it ideal for powering hybrid devices requiring both indoor and outdoor usage.

LoRa Wide Area Network, with many kilometre range, allows minimal gateway infrastructure costs compared with competing short-range wireless (WiFi, BLE, EnOcean) enabling easier installation, maintenance and better affordability and minimising electrical infrastructure in hazardous areas. This work has focused on sensor development to optimise wavelength selectivity for methane, performance optimisation to minimise sensor power usage, integration of PV and hybrid LoRa/BLE components novel power management and storage architectures (incl. supercapacitors) and node-level strategies to customise energy-per-measurement, giving full control of the trade-offs on measurement frequency under lowest light conditions.

2. SENSOR OPTICAL SYSTEM DESIGN & PV MODULE

The methane sensor optical system is comprised of the following components; 2-mirror parabolic reflector, IV-VI (or III-V) semiconductor light source, IV-VI semiconductor light detector and multilayer optical interference filters. The 2-mirror parabolic reflector is manufactured by injection moulding. The mirror optical surfaces are sputter coated with gold (Au) in order to achieve >98% optical reflectance in the 2.5 μm – 5 μm wavelength band, covering the 3.3 μm methane absorption band. The light source is a mid-IR photoluminescent based light emitting diode composed of band gap engineered $Pb_{1-x}Cd_xSe$ thin films growth by sputtering and sensitized in a post deposition annealing thermal diffusion procedure. A detailed description of the IV-VI mid-IR light source fabrication procedure and performance can be found in [4]. The light detector is composed of a IV-VI semiconductor pn-junction grown by sputtering and has a photoresponsivity of 300 mA/W.

Three thin film optical interference filters are included; a wide bandpass filter centered at 3.3 μm, providing blocking of H_2O molecular absorption wavelengths centered around 2.8 μm, a narrow bandpass filter centered at 3.3 μm to provide selectivity of the methane absorption band for the signal detector, and narrow stop band filter to reject the 3.3 μm methane absorption band wavelength to provide a reference channel. The source and detector are housed in TO-46 and TO-39 cans respectively. The TO-39 detector can is capped using the wide band pass filter, and the narrow band pass and stop band filters are located above the signal channel detector and reference channel detector respectively. Thin film optical interference filters are grown using microwave plasma assisted reactive DC magnetron sputtering and are composed of Ge/Nb_2O_5 multilayers. providing minimal spectral shift over sensor operational range -20^{o}C to 40^{o}C [5]

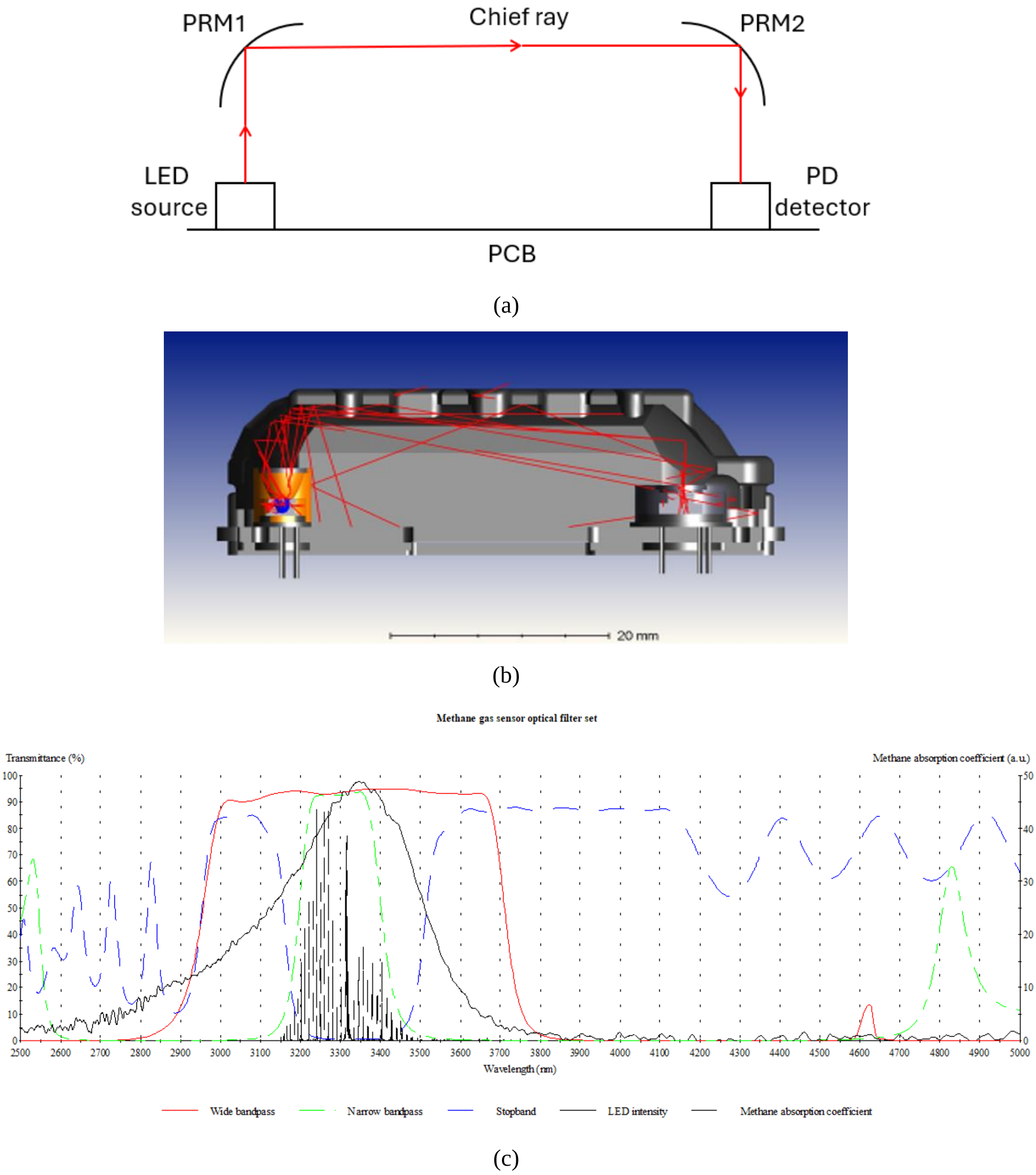

Figure 1. (a) Simplified methane gas sensor optical layout displaying LED light source, parabolic reflector mirror 1 (PRM1), parabolic reflector mirror 2 (PRM2), chief ray, photodiode (PD) detector and printed circuit board (PCB). (b) 3D model cross section of optical methane gas sensor and optical ray trace. (c) Optical transmittance curves for the optical filter set included in the methane gas sensor, including the IV-VI light source spectral emission and methane gas absorption coefficient.

3. EXPERIMENTAL SET-UP

Under indoor light conditions, the Lightricity PV energy harvesting module is 30–35% efficient (corresponding to > 20 µW/cm^2 at 200 lux under artificial lighting). The Lightricity PV module retains performance from -35°C to +150°C whereas lithium-ion batteries work best at 15°C to 35°C and can't recharge below 0°C. In addition, the PV module is a non-sparking energy source and therefore supports ATEX compliance which is critical for methane gas sensor deployment in the oil and gas industry.

F

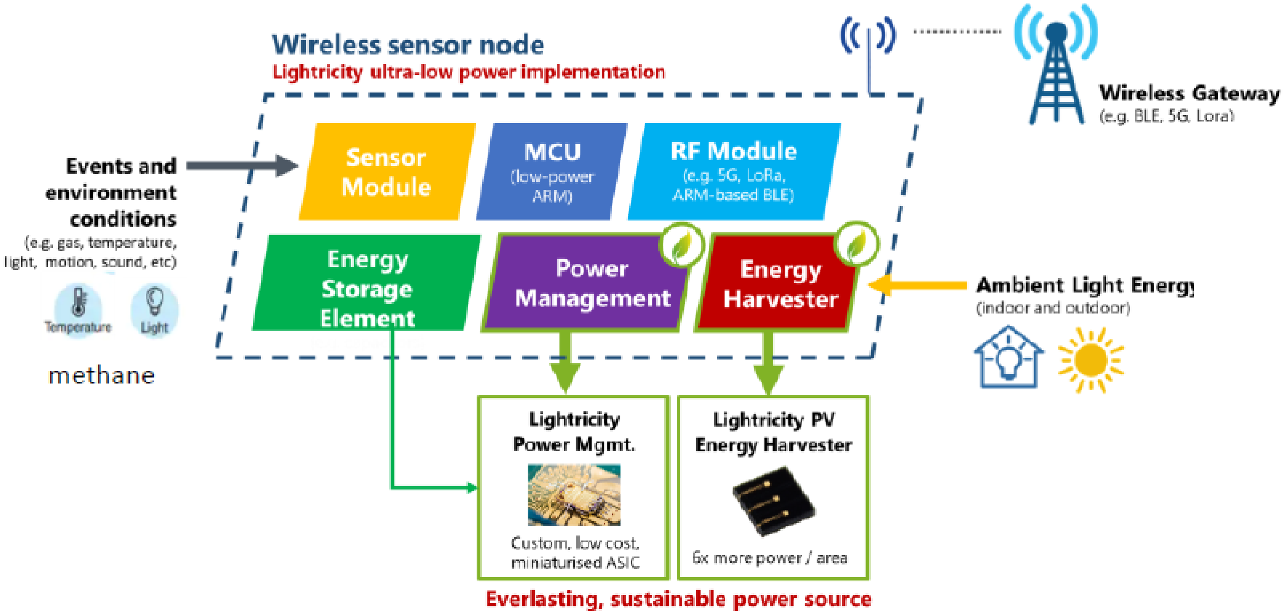

Figure 2. Light-powered wireless sensor node architecture.

The methane gas sensor LED was driven at an operating frequency of 3 Hz at a pulse width of 13 µs. The sensor current draw is around 15 µA at a supply voltage of 3.3 V, provided by the PV module. This ~50 µW power consumption is approximately 2.3x lower than the current state-of-the-art low power methane sensor technology, and is therefore compatible with powering from Lightricity Ltd's PV energy harvesting unit and wireless BLE data transfer. Testing of the sensors was conducted to evaluate the performance and reliability of a board equipped with the CH_4 gas sensor, temperature sensor and relative humidity sensor. Throughout all testing, an LED lamp was on in the climatic chamber, this serves the purpose of providing a stable power source for the sensors, ensuring that data collection is not affected by power fluctuations or interruptions. All data was transferred wirelessly through BLE at a Baud rate of 115200.

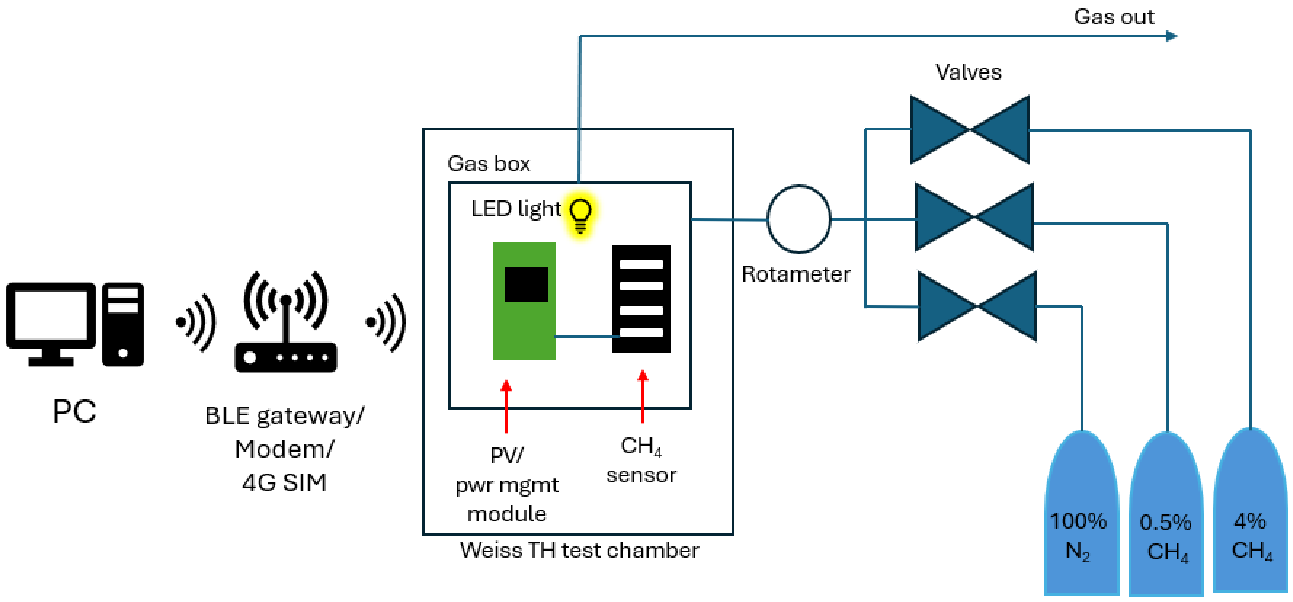

Figure 3. Schematic of experimental test set-up. The sensor and PV module were located inside a small transparent gas box. The box was situated inside a Weiss WKL-34 climatic chamber with temperature and relative humidity control and internal LED lamp. Various concentrations of methane were flown into the chamber in order to test the wireless sensor’s performance.

To assess the board's capabilities in measuring temperature, relative humidity (RH), and gas levels within the climatic chamber, a systematic approach was adopted to induce controlled changes in environmental parameters, and the sensor responses were closely monitored. Throughout the tests, real-time data from the board's sensors were logged for subsequent analysis on Datacake IoT platform. The adjustments ranged from low to high levels, mimicking different environmental scenarios to ensure the sensor's adaptability. Throughout all tests, a light was on in the climatic chamber, this serves the purpose of providing a stable power source for the sensors, ensuring that data collection is not affected by power fluctuations or interruptions.

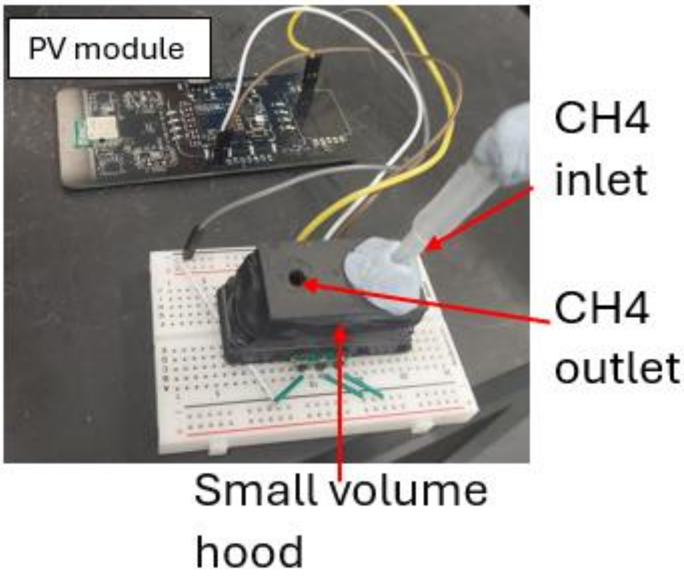

Figure 4. Image of methane gas sensor and PV module which was mounted in the Weiss WKL-34 climatic chamber.

4. EXPERIMENTAL RESULTS

A sensor test conducted in an environmental chamber with controlled CH_4 concentration steps. The general trend shows a distinct pattern of methane concentration levels. Concentration steps of 0%, 3.5%, 1%, 3.5%, 2.5%, 1.5%, 0.5%, and 0%. A small volume hood was employed in the gas sensing test to facilitate rapid turnovers of gases within the environmental chamber. This allowed for precise and controlled variations in methane concentrations during the experiment.

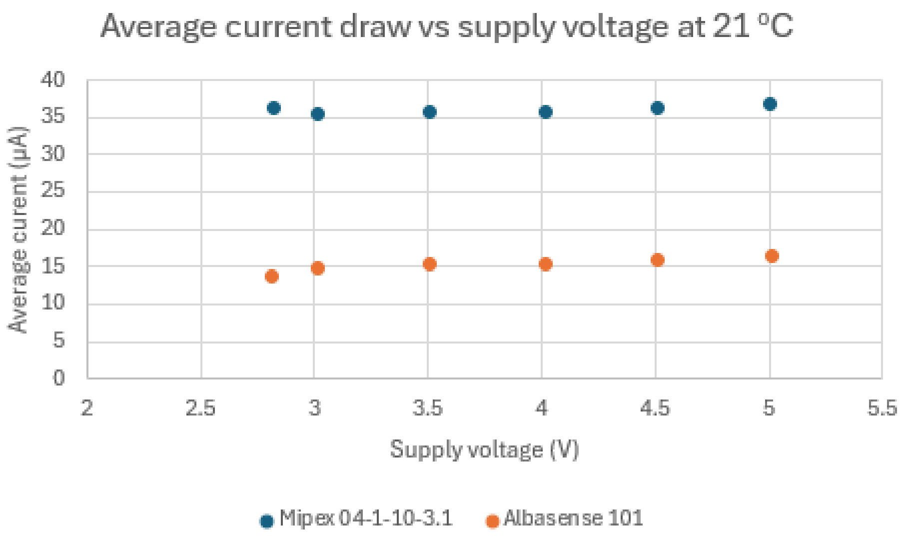

Figure 5. Sensor current draw versus supply voltage comparison with the current state-of-the-art [6].

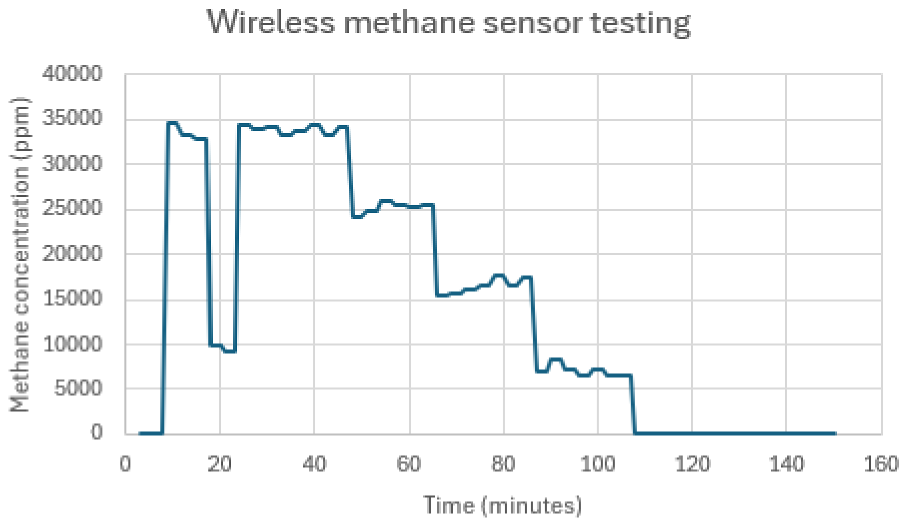

Figure 6. Wireless methane sensor response to varying concentrations of methane, demonstrating successful wireless transfer of data during powering by PV module.

This demonstrates that the PV module and energy harvesting provides enough power for the sensor to operate under ambient conditions, measuring a range of methane concentrations below the lower explosive limit (LEL). Next, temperature testing was carried out in order to assess the functionality of the temperature sensor during wireless operation. The methane concentration was set to 0% and the temperature was ramped from 40°C to -20°C. The temperature data exhibits distinct phases over the recorded time. The sensor test was conducted in an environmental chamber with specific temperature steps (30°C, 40°C, 20°C, 0°C and -20°C). Beginning with a stable baseline around 30°C, the sensor shows a gradual increase with the rising temperature steps. Subsequently, the sensor exhibits a gradual decrease and stabilisation, indicative of its adaptation to the lower temperatures during the drop to 0°C and -20°C steps. The board firmware update allowed the sensor to record data at even lower temperatures, expanding the operational range. Figure 7 demonstrates that the sensor onboard temperature sensor can function powered by the PV module. Temperature monitoring will be critical to sensor operation, as the LED spectral response will vary in intensity at different temperatures. The sensor's firmware contains a temperature compensation algorithm that varies the LED power according to the measured temperature in order to stabilize the sensor's accuracy across a wide range of temperatures.

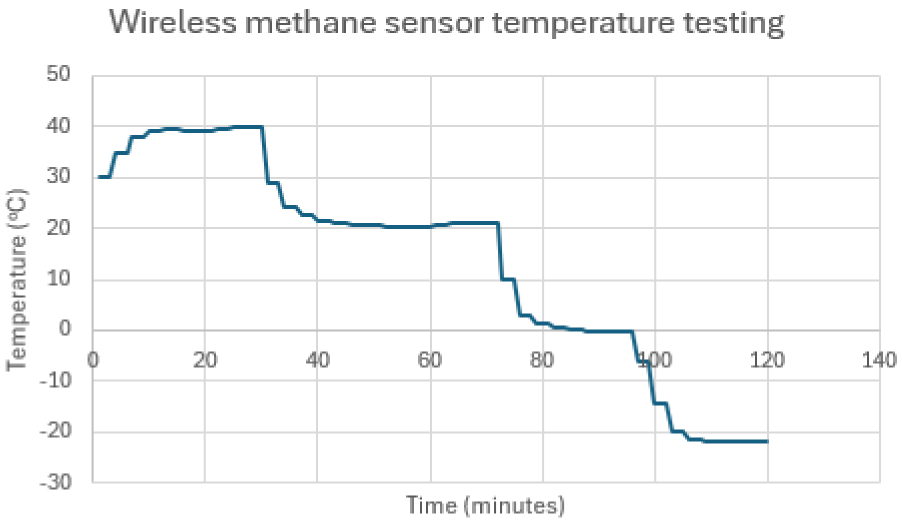

Figure 7. Wireless methane sensor's temperature sensor response from -20 °C to + 40 °C.

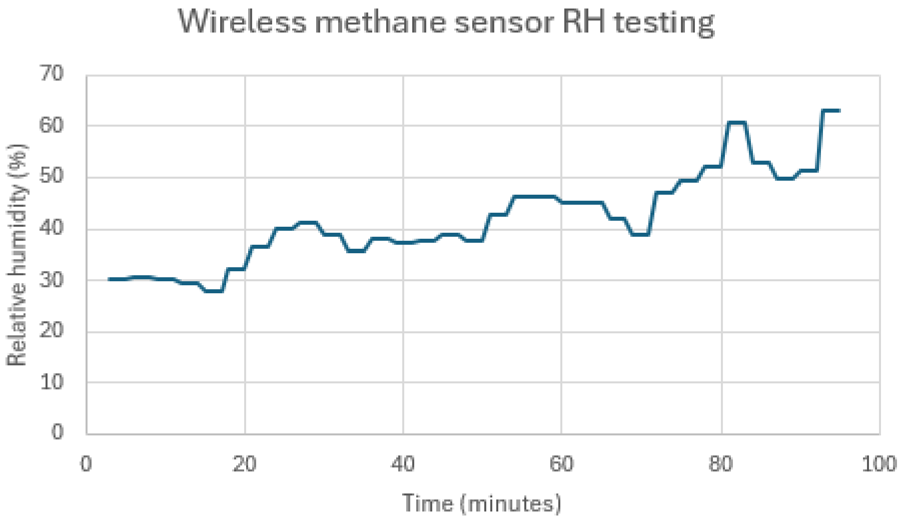

Figure 8. Wireless methane sensor's RH sensor response from 30% RH to 60% RH.

A sensor test was conducted in an environmental chamber with relative humidity (RH) steps of 30%, 40%, 50%, and 60%. The sensor readings stabilise at each targeted RH level, demonstrating the sensors effective measurement of the environmental conditions. Initially stable, the humidity exhibits distinct transitions corresponding to shifts from 30%, to 40%, 50%, and 60% RH levels.

The successful tracking and alignment of the sensor readings with the changes in temperature, relative humidity, and methane concentrations signify the performance of the sensors within the climatic chamber. The close correspondence between the set levels and the sensor responses demonstrates the accuracy of the sensors integrated into the board.

5. CONCLUSION

The ultra-low power methane sensor was demonstrated to be compatible with wireless operation when powered by a Lightricity PV energy harvester and power management module. Successful communication, via BLE, of methane concentration, temperature and relative humidity was demonstrated at a sensor power consumption of around 50 µW and a supply voltage of 3.3 V. Wireless operation remained stable over the 0 – 35000 ppm methane concentration range (typical accuracy ±3%), -20 °C to +40 °C temperature range and 30% to 60% relative humidity range. This demonstrates the sensor's potential suitability for network-scale deployment of wireless optical methane gas sensors on oil & gas fields, oil refineries and any industrial environment where methane production poses an environmental and safety hazard.

ACKNOWLEDGEMENTS

We would like to thank InnovateUK (grant number 10034903) and UWS Vice Chancellor Fellowship for the support. Authors would also like to thank West of Scotland Science Park (Glasgow, UK) for the spectral PL measurements. Authors acknowledge funding from InnovateUK, project reference 10034903 .

REFERENCES

[1] S. Solomon *et al.*, “Climate Change 2007: The Physical Science, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.,” 2007.

[2] Z. D. Weller*, S. P. Hamburg, and J. C. Von Fischer, “National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems,” *Environ. Sci. Technol.*, vol. 54, no. 14, pp. 8958–8967, 2020, doi: 10.1021/acs.est.0c00437.

[3] M. Kauer and M. Bellanger, “Lightricity.co.uk,” 2023. https://lightricity.co.uk/ (accessed Mar. 20, 2024).

[4] G. Mcgann, L. Fleming, D. Hutson, E. Waddell, and D. Gibson, “Band Gap Engineering of Pb1-xCdxSe Thin Films Providing Mid-IR Photoluminescent-Based Light Emitting Diodes for Use in Nondispersive Infrared Gas Sensors,” *IEEE Sensors Lett.*, vol. 7, no. 9, pp. 1–5, 2023, doi: 10.1109/LSENS.2023.3307081.

[5] J. Pomfret *et al.*, “Microwave Plasma Assisted Magnetron Sputtering of Infrared Multilayer Thin Film Bandpass Filters for application in non-dispersive infrared gas sensors,” *Opt. InfoBase Conf. Pap.*, pp. 6–8, 2022, doi: 10.1364/oic.2022.thc.7.

[6] “Mipex Technology.” https://mipex-tech.com/ (accessed Mar. 20, 2024).