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HYPERIMAGE

A universal spectral imaging sensor platform for industry, agriculture, and autonomous driving.

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SWIR illumination sources and drive circuits

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AUTHOR

Author	Institution	Contact (e-mail, phone)
Ross Stanley	4K-MEMS	r.stanley@4kmems.ch

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Project Manager	Marina de Souza Faria	29/06/2025
Project Coordinator	Alexander Kabardiadi-Virkovski	29/06/2025

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Point of Contact	Name: Ross Stanley Partner: 4K-MEMS SA Address: Phone: +41 78 6830494 E-mail: r.stanley@4kmems.ch
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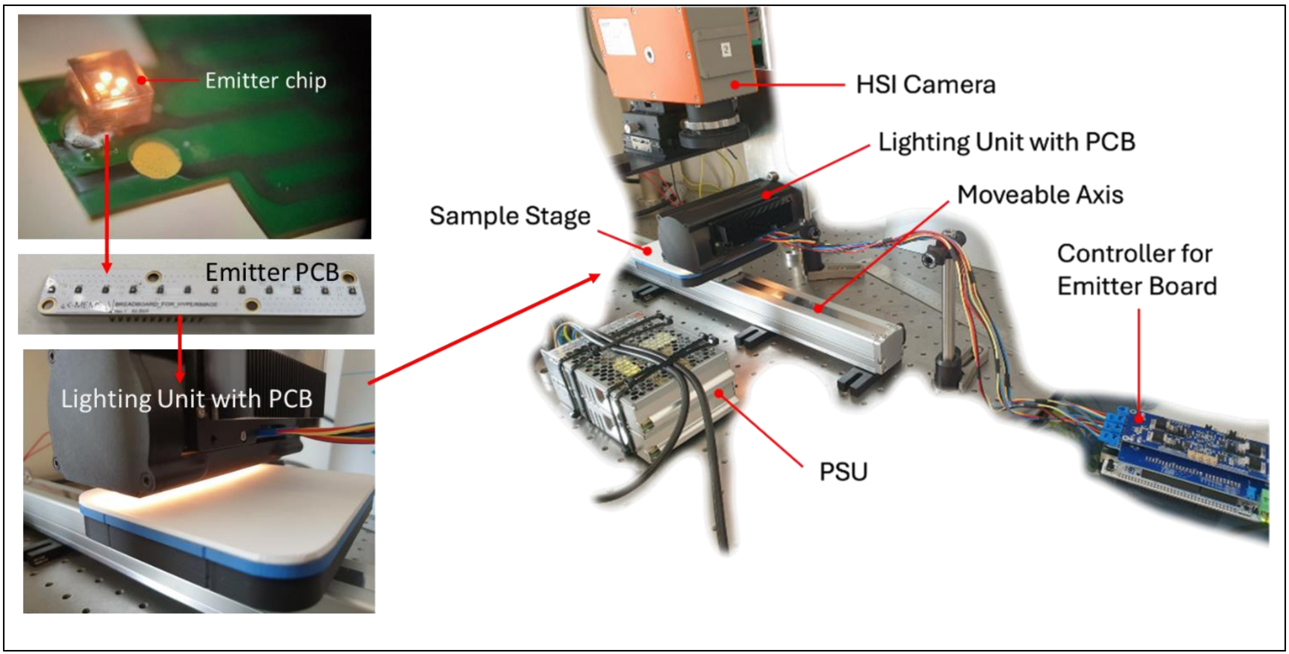
DISCLAIMER

Executive Summary

Here we demonstrate a working SWIR hyperspectral imaging lamp based on novel 4K-MEMS emitter technology, inside a diffusive lamp built by DIVE along with the control electronics built by 4K-MEMS. The system was tested and is close to the specifications as laid out in WP1.



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1. Introduction

This deliverable is part of WP2. Task2.1 Smart Illumination and Light source solutions with partners 4KMEMS & DIVE.

WP2.1 is based around the development of custom illumination for SWIR range light sources. The advantages of using 4K-MEMS emitters is that they have tungsten light bulb performance in an LED-like package.

The gaol of this deliverable is to show that we can build SWIR illumination lamps based on 4K-MEMS emitter technology.

We structured the work as follows.
WP1 gave us the specifications with respect to the number of devices per unit length. It turns out that 1 device per cm with 4 emitters per device would give a light intensity as required for semiconductor analysis (Infineon use case).

The original measurements were made with emitter dies packaged in ceramic packages. As this is not a scalable technology, 4K-MEMS adapted its technology, to achieve wafer scale packaging (WP2.1). With wafer-scale packaging the dies can be transferred directly from dicing tape to PCBs. The development of this technology is a key part of WP2.1 and significant resources were used to achieve this.

In parallel, we had to design and build the drive electronics to power the emitters based on electronics that we were building to test the emitters in the lab. As explained below the electronics is quite complex due to on one hand the special needs of the emitters and on the other hand to the multiple functions that we wanted the electronics to perform.

The lamp design was decided by DIVE based on existing lamps and the results of WP1. It was decided to make a modular PCB 10cm long, with 12 emitter dies.

The emitters were mounted on the PCBs, fitted to the lamps and tested in the visible and in the IR to see if they reach specifications.

We worked with three sizes of lamps.

Lamp	# of PCBs	# dies	# emitters	Max Power Consumption (W)
(A) Small lamp	1	12	48	4.6
(B) Full lamp	4	48	192	18.4

The deliverable specifications was to demonstrate 4 lamps with more than 80 emitters. For real world applications, full lamps with 192 emitters would be more suitable. Due to supply issues, we decided to only show case the small lamps these includes the emitters, the PCB, the diffusive lamp housing, the electronic drivers, all assembled and tested under normal operating conditions. The design of the full lamps as well as the drive electronics were completed at the same time.

2. Results and Discussion

Describe here all the achievements and how did you obtain them, possibly with visual contents like pictures, schemes, graphs, etc.

2.1. Emitter Chips (4K-MEMS)

2.1.1. Chips

The first sub-task was to make wafer-level packaged chips. This is exceptionally challenging as design includes through glass vias to get current to the MEMS emitter, the actual MEMS emitter, which is a free floating membrane suspended in vacuum, a lid with a getter to maintain a good vacuum. All this needs to be assembled together at a wafer level with no leaks. Even a low background pressure of an inert gas would render the devices unusable due to thermal losses through the gas – the MEMS are suspended just 4 microns from the surface so the thermal shunt is significant at pressures down to 10mbar.

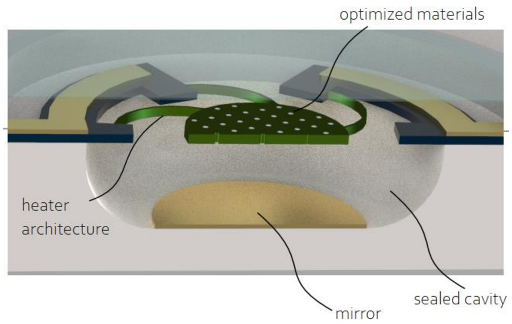
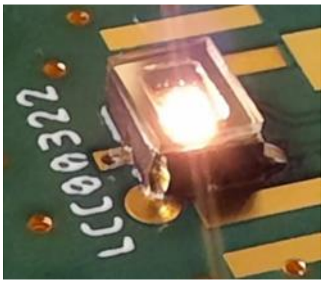
	

Figure 2.1.1(a) : The principle of the 4K-MEMS emitter. A membrane is suspended in a vacuum by heater arms which both heat the device and act as springs to absorb temperature changes.	Figure 2.1.1(b): A 4K-MEMS emitter under operation. This device is mounted in a ceramic package, wirebonded and sealed with a lid under vacuum. The package size is 2.4 x 3mm.

2.1.2. Manufactured devices

The emitters were designed by 4K-MEMS and manufactured at a wafer scale by Inchfab, California. What was achieved here, was to make MEMS emitters on a base wafer with vias for electrical contact and then bonded it to a cap wafer under vacuum. This packaging process allows us to package all the devices at the same time (wafer-level packaging). In addition, we are able to dice the wafer into individual chips without lose of space (chip scale packaging). Figure 2.1.3 shows the backside of a completed waver, showing the pads used for bonding to the PCB as well as the size of the device. Figure 2.1.4 shows working chips directly mounted onto solid and flex PCBs. Up to four emitters can be made to function in a single package. The chips with 4 emitters were subsequently mounted on PCBs for use in the lamps.

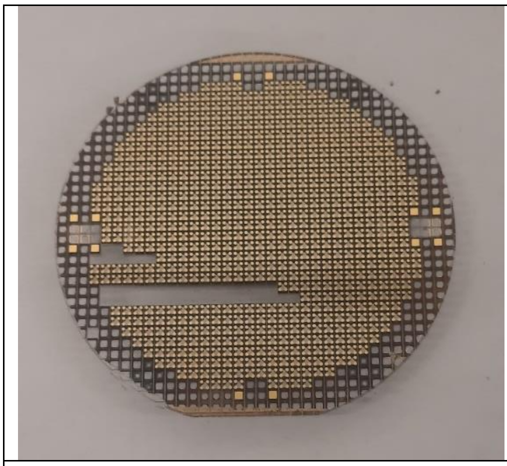


Figure 2.1.3(a): inch wafer containing 720 emitter dies. The gold dots are the pads used for bonding to PCBs.

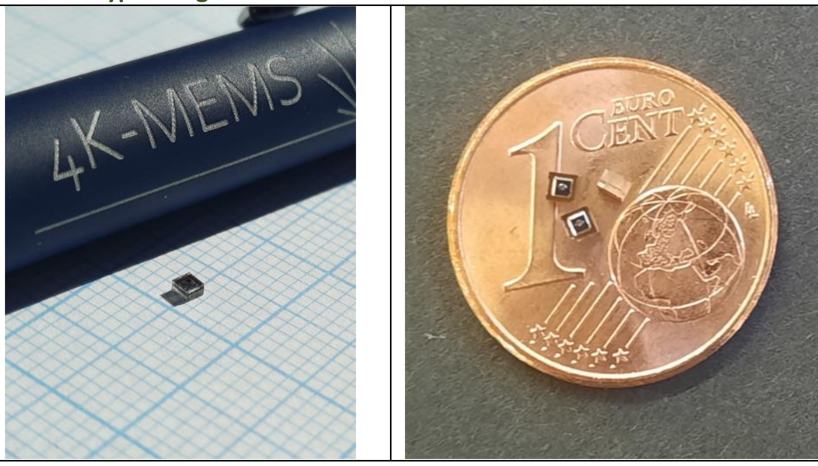
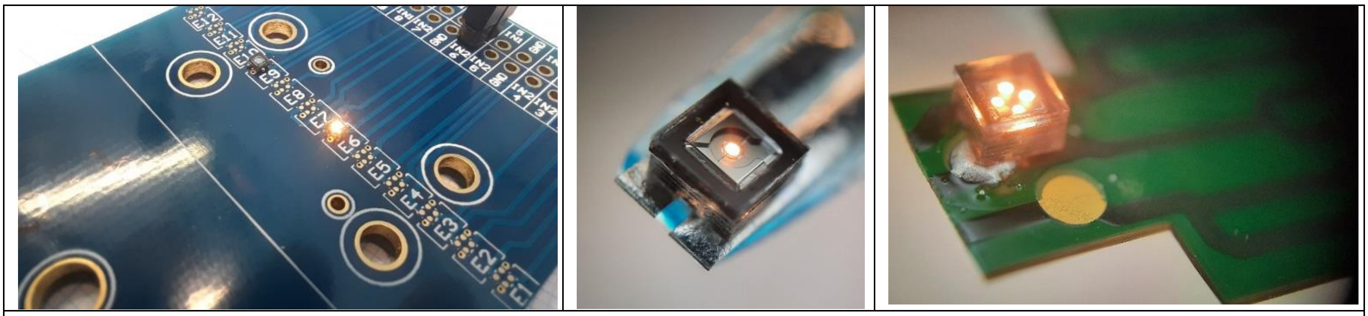


Figure 2.1.3(b): A device shown in comparison to graph paper middle and Euro cent left. The die is 1.4 x 1.4 x 0.8 mm.



Figure(2.1.4) Examples of devices mounted on standard PCBs, to the right and on flex PBCs (middle and left). The dies have either 1 or 4 emitters per package.

2.2. Drive Electronics (4K-MEMS)

At 4K-MEMS we have been developing test benches to measure 10s to 100s of devices at a time. The electronics is quite complex as we want to perform multiple functions.
First of all, the device lifetime is limited under standard DC drive, due to electromigration, so we use a square wave AC carrier instead. Secondly, we would like to monitor the current and voltage going to the devices under test, so we have a four-point set-up. Thirdly, we want to have full freedom in the type of modulation we impose on the AC carrier signal. Finally, we want to control all this via a computer.

Electromigration: The flow of current through a wire at high current density and at high temperatures can lead to a physical displacement of material in the direction of current flow. Electromigration is a well-known problem in tungsten lamps which are normally run under AC operation which over comes this. In a household lamp the current/voltage is oscillating with a sine form, which is just faster than the eye response, in addition due to the slow response of a filament lamp it does not completely cool down in each cycle, together two effects means that we do not notice the flickering. In contrast the rise time of the 4K-MEMS emitter is in the order of 5-10mS. So, in order for them to by always on the frequency of oscillation should be in the kHz range and the signal should be a square wave. We use the >1KHz square wave as a carrier on which we impose other functions, such as modulation. As we want to have full control of the modulation that we put on the emitter for testing, the electronics was designed to include that. The on-board microcontroller manages all outputs, carrier frequency, modulation depth, amplitude, etc. and has a local OS which can be controlled through a USB port.

In order to monitor the output, there is a complete measurement system to measure current and voltage of each channel. Due to the very low resistance of the emitters when cold, a four-probe system is used to measure the voltage and give realtime feedback in order to stabilize the output.

Specification	Symbol	PRECISION 12CH EMITTER DRIVER	Unit
General			
Number of Channels	*CH*	12	#
Supply Voltage	V_{sup}	>5	V
Supply Current	I_{sup}	>12	A
Communication		Serial (USB)	
Driver outut (per channel)			
Output voltage	$V_{\#}$	0-3	V
Voltage accuracy	$V_{\#err}$	<2	mV
Voltage resolution	V_{res}	<1	mV
Max Voltage overshoot	V_{over}	<5	mV
Max Output current	$A_{\#max}$	1	A
Ramp rate	V_{ramp}	10'000	V/s
settling time	t_{settle}	<2	ms
Inversion frequency	f_I	DC-40'000	Hz
Feedback (per channel)			
Current Measurement accuracy	$A_{\#}$	1	mA
Driver Temperature	*T*	-20 to +80	°C
I2C and/or SP2			
Other			
format		tray, stackable	
continuous operation		>10'000	hrs

Table 2.1 Target specifications for the driver electronics.

Finally, the 4K-MEMS emitters devices are voltage controlled but require relatively high currents per emitter (120 mA) as we will be driving more than 80 emitters, the total current coming from the electronics will be quite large, and a large amount of heat needs to be dissipated.

While functionally of the drive electronics is "overkill" for driving the lamps, it is still the simplest way to control the lamps and is very useful for tests as each the multiple channels can help in making the light output more uniform.

2.2.1. Driver architecture

An overview of the architecture is provided in 2.2.1. This setup is not the most compact or energy efficient, but it provides a high degree of flexibility and results in the high-quality output signal needed for this project. The final footprint is not yet fixed but the individual daughter boards will be rather small and can be updated or replaced as needed. All heat generated will be in these daughterboards, which will have cooling elements added if needed. It is anticipated that for standard loads (pulling under 300 mA/channel) this will not be needed. In specific configurations where multiple chips are driven in parallel each channel can provide up to 1000 mA.

The motherboard will be dimensioned for rack mounting such that arrays can be mounted in a standard setup, leaving sufficient space for airflow to avoid overheating. A temperature sensor is included on each daughter board to enable a safety shutdown option. The array of 12-channel motherboard mounted in the rack could all be powered individually or by a central power block, dimensioned accordingly.

The initial software will support only a serial communication for controlling the board. A Linux like terminal command will be implemented, commands can be executed manually by a RS323 terminal or in connection with a host Python, Matlab, Mathematica, Sysquake, or LabView software.

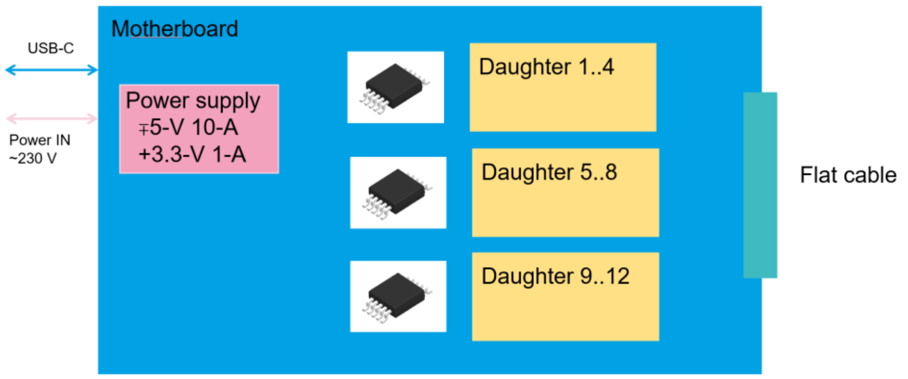
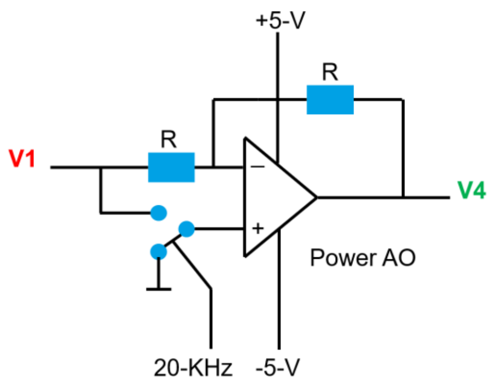


Figure 2.2.1. Electronics Drive Architecture.

Voltage Inversion

The voltage inversion is controlled by a switch that modulates the non-inverting input of the power amplifier. A sketch of the schematic is illustrated in **Error! Reference source not found.** 2.6, along with the spice-simulated output. In this implementation V1 is the envelope function, derived from the DAC of the microcontrollers and the inversion frequency is set to 20 kHz.

The inversion signal switches a solid-state switch, alternating the noninverting input from ground to the drive voltage (V1 in **Error! Reference source not found.** 2.2.2). When the noninverting input is at GND the output of the amplifier is *-V1*, while if the When the noninverting input is at *V1*, then the output is at *V1*. Critical for symmetric output are perfectly matched input and feedback resistors labelled as *R*.



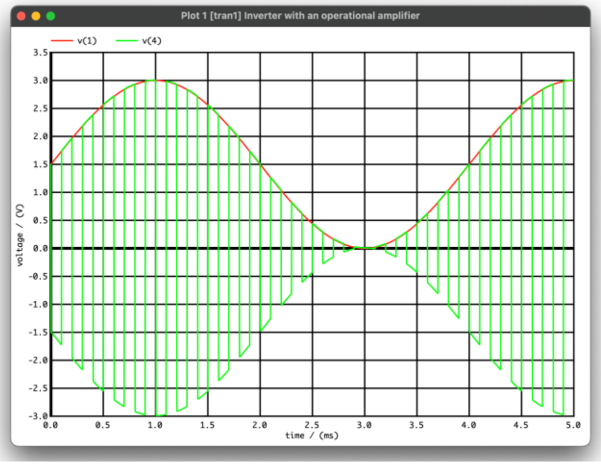


Figure 2.2.2 Left: Power amplifier with inverter schematic. Right: Spice simulation illustrating the envelope function in red and the modulated signal in green.

Figure 2.2.3 shows a completed 4 channel controller. The 4-channel controller is designed to drive the small lamp with one PCB and 12 emitter chips.

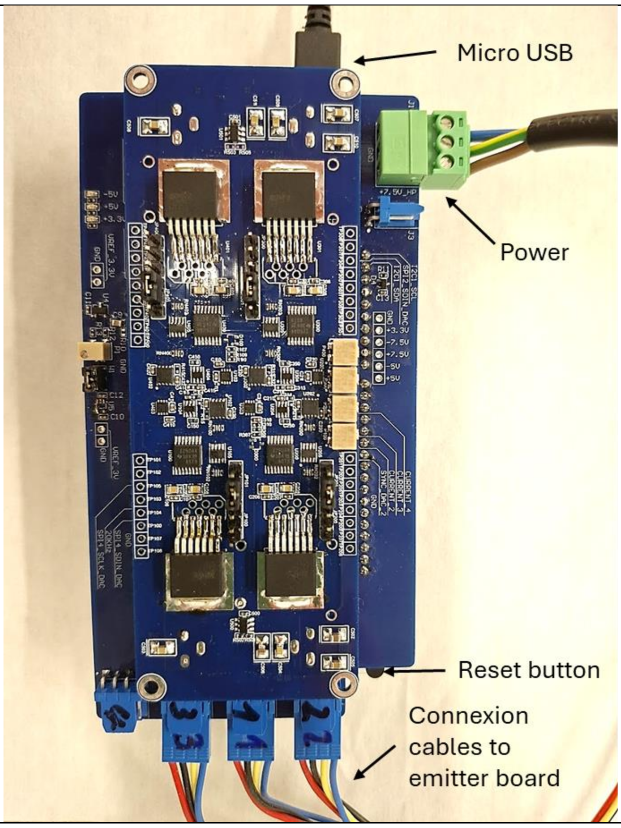


Figure 2.2.3: 4 channel controller which can be used to power one PCB (12 emitter dies arranged in 3 sets of 4 dies in parallel)

2.2.2. 12 channel controller

Based on the experience of building the 4 channel controls a 12-channel device was built for the full lamp. The solution is based on the following elements:

- Motherboard: Handles communication and power, supplied by two power bricks that provide the bi-polar voltages (±5 V 10 A for the 12 power amplifiers and +3.3 V, 1 A for the digital electronics)
  The motherboard includes 3 CPUs, 4 STMH743 microcontrollers, one for communication, three to interface with the three daughter boards.
  3 x UART collectors routed in 1 USB channel for controlling and for collecting data to / from the 12 channels
  The motherboard includes a 48+ flat ribbon cable interface for 12 4-point connections.
- Three Daughter boards: Include the conditioning electronics, i.e. the power-amplifiers, feedback and filtering needed to turn the 16-bit DAC output from the motherboard into high precision, high current channel output. The selected power amplifier is not a rail-to-rail device. That means that a cooler has to be considered

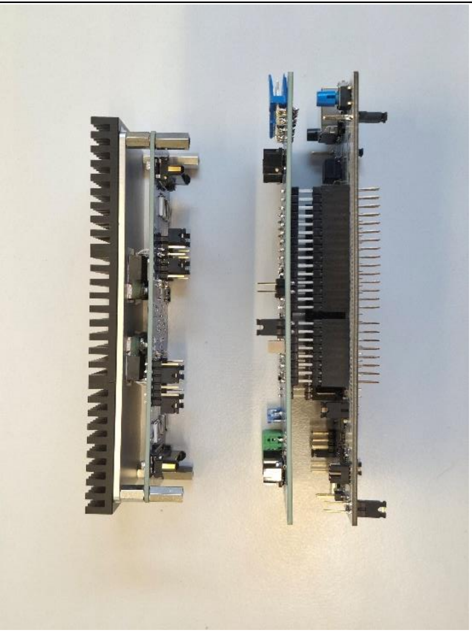
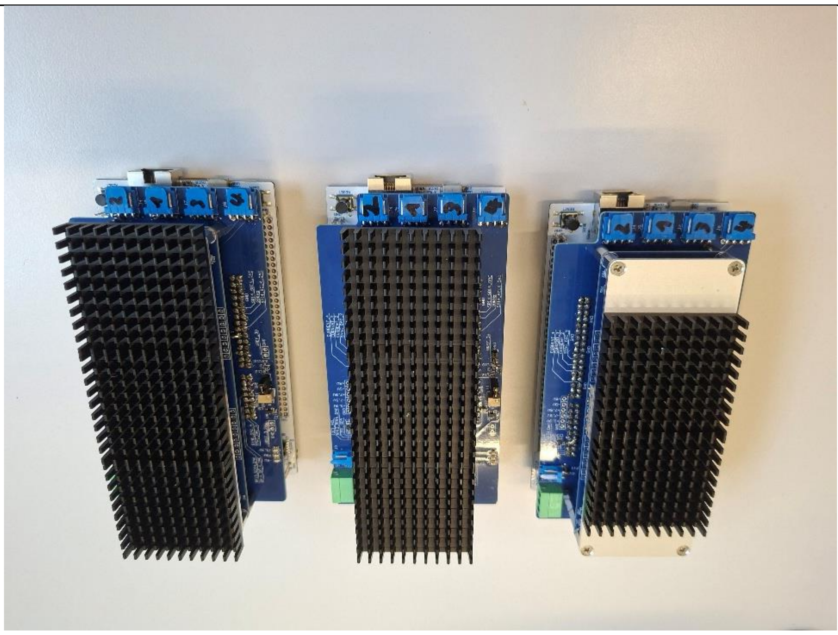
	

Figure 2.2.4 (a) A four channel board with heat sink. Daughter board with heatsink is shown on the right. Motherboard and power controller on the left.	Figure 2.2.4 (b) Three completed four channel boards designed for use with the large lamp.

2.3. Emitter PCB design (4K-MEMS)

Together with DIVE we designed a PCB to hold 12 emitter dies. We wanted to scale the lamp from a single board with 12 emitter dies (48 emitters) to a lamp with 4 boards, 48 dies. At the same time, we wanted to use the twelve-channel controller. For this we grouped the dies into 3 groups of 4 dies in parallel. The emitter dies are voltage driven hence the preference to run them in parallel. LEDs are current driven so they are usually run in series, leading to lower currents but higher voltages. The PCB was designed with this in mind. The emitter dies are mounted below a heatsink which is added later. A 12-channel connector is used where we were two of the contacts in parallel so that only three driver channels are used per board.
The PCB has insulated screw insets so that it can be attached to the lamp housing.

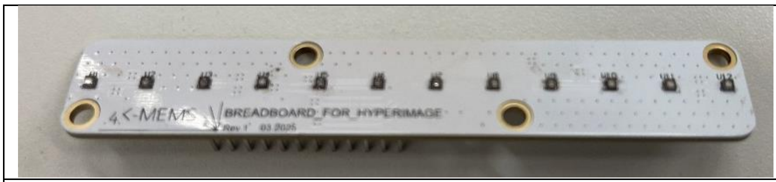


Figure 2.3.1 showing a fully mounted PCB with 12 emitter dies.

2.4. Lighting Unit (DIVE)

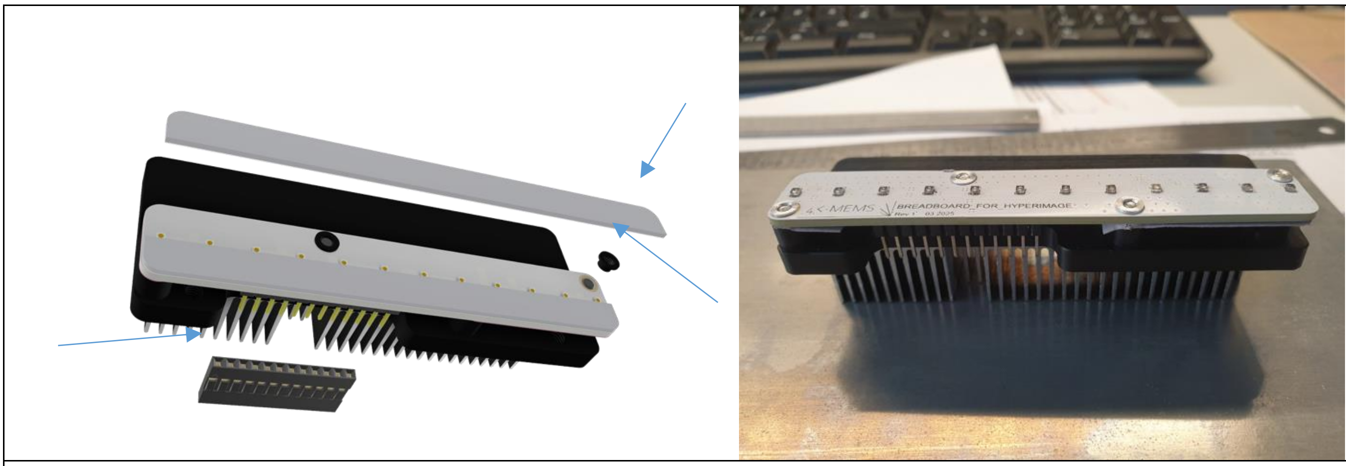
As part of WP2, dive is developing a lighting unit in collaboration with 4K-MEMS for the investigation of electronic components (use case with IFBIP), which will be integrated into the hyperspectral imaging system. The goal of all lighting systems used for hyperspectral imaging is to produce a uniform and diffuse light, with adequate intensity in the wavelength region of interest. The region is defined by the cameras used, and in this case ranges from 400 to 1000 nm (VNIR) and from 1000 to 1600 nm (SWIR). The 4K-MEMS emitters are designed to have maximum emission in the SWIR region, but it is questionable whether they can be used for both wavelength regions.

The currently existing lighting system uses halogen lamps, which provides good spectral coverage but comes with limitations such as high-power consumption, larger physical size and high temperatures. 4kMEMS emitters offer a unique combination of benefits that are particularly valuable for hyperspectral lighting systems. These emitters deliver a broad and continuous emission spectrum, especially in the SWIR range - while being packaged in a form factor similar to LEDs. Their compact design allows easy integration into optical setups, while their lower power consumption and low operating temperature make them highly suitable for energy-efficient applications.

Small Lighting Unit

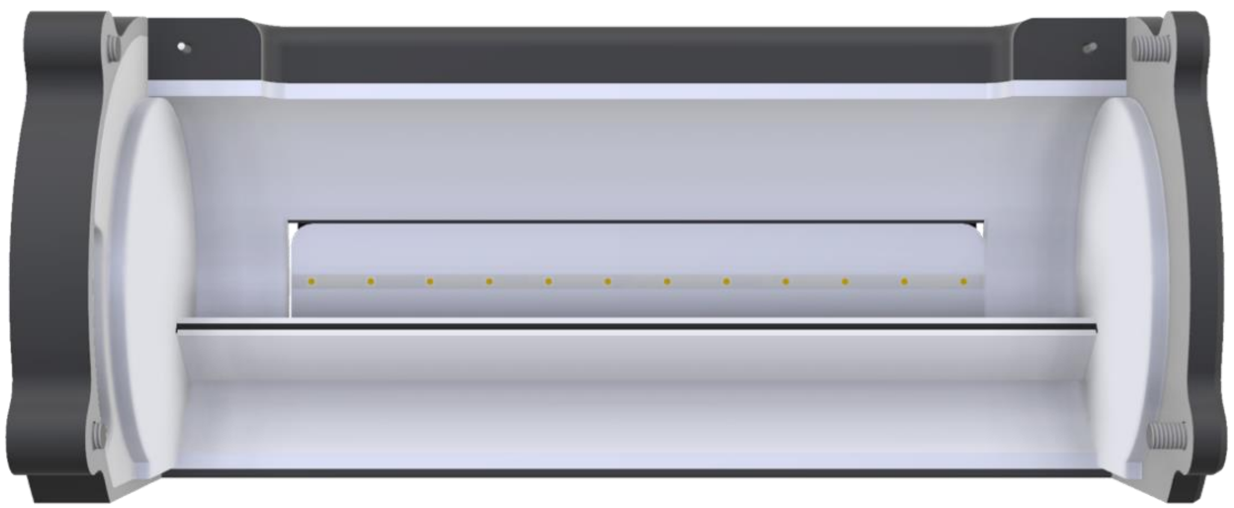
The large lighting unit has been designed to fit into the VEpioneer hyperspectral imaging system from DIVE. Due to production challenges and limited supply, a smaller lighting unit with a 10 cm PCB containing 12 emitter dies was developed for prototype testing. It is capable of illuminating samples with a maximum width of 121 mm instead of the planned 300 mm. Due to the identical light diffusion functionality of the small lighting unit compared to the large one, which is supposed to operate with total of 4 PCB boards the results can also be used to draw conclusions about the usability of the large lighting unit. This large size unit can also be scaled down to fit just two emitter boards.

The emitter board is designed with several features to optimize optical performance A surface-mounted connector is placed on the backside of the board to keep the front side clear, allowing for unobstructed optical output. Low-profile bolt inserts are used and can be screwed in from the rear, minimizing obstruction on the front surface. To enhance diffuse reflection, optically reflective PTFE foil strips are applied to the front of the board. Passive cooling is implemented using a heatsink to ensure low noise operation. However, due to production constraints and the prototype nature of the first emitter board, it was not possible to evaluate the actual thermal requirements. As a result, the current heatsink is likely oversized and presents potential for reduction in future iterations.

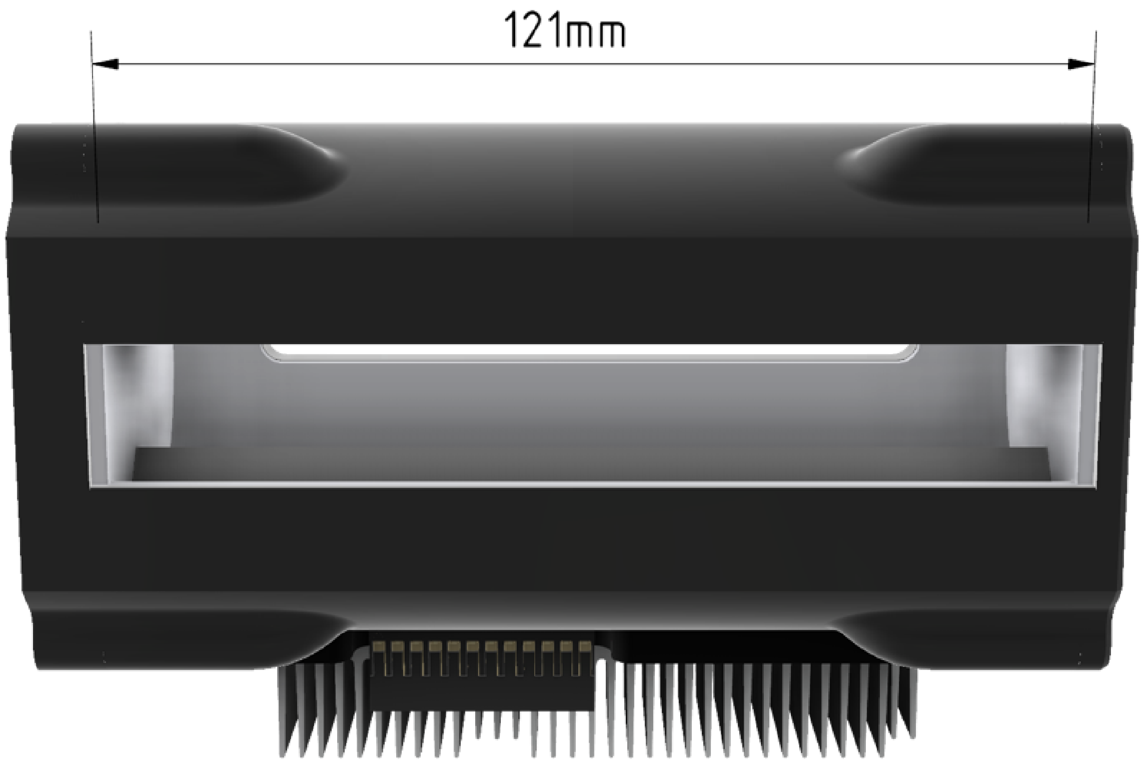


Emitter board assembly. Schematic view (left) and real image (right).

The emitter board assembly is installed into a custom 3D-printed housing, as shown in the figures below. The housing is specifically designed to provide uniform, diffuse illumination of the samples while allowing the camera to view them through an integrated slit and perform line-scan imaging.



Interior view of the small lighting unit with an emitter board. The interior of the housing is fully lined with PTFE to maximize surface reflection.

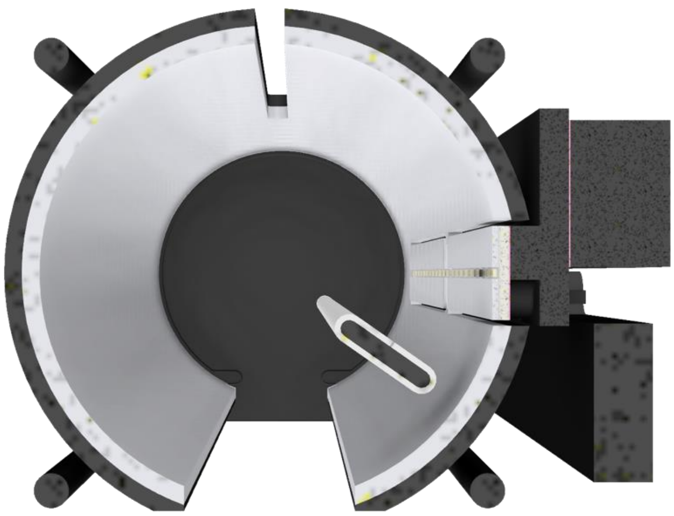


Small lighting unit underside with exit slit for diffuse light and maximum possible field of view. Passive cooling is mounted on the backside of the emitter board.

Full Lighting Unit

Full lighting unit equipped with four emitter boards. The overall dimensions and mounting points follow the VEpioneer standard, ensuring compatibility with existing system components.

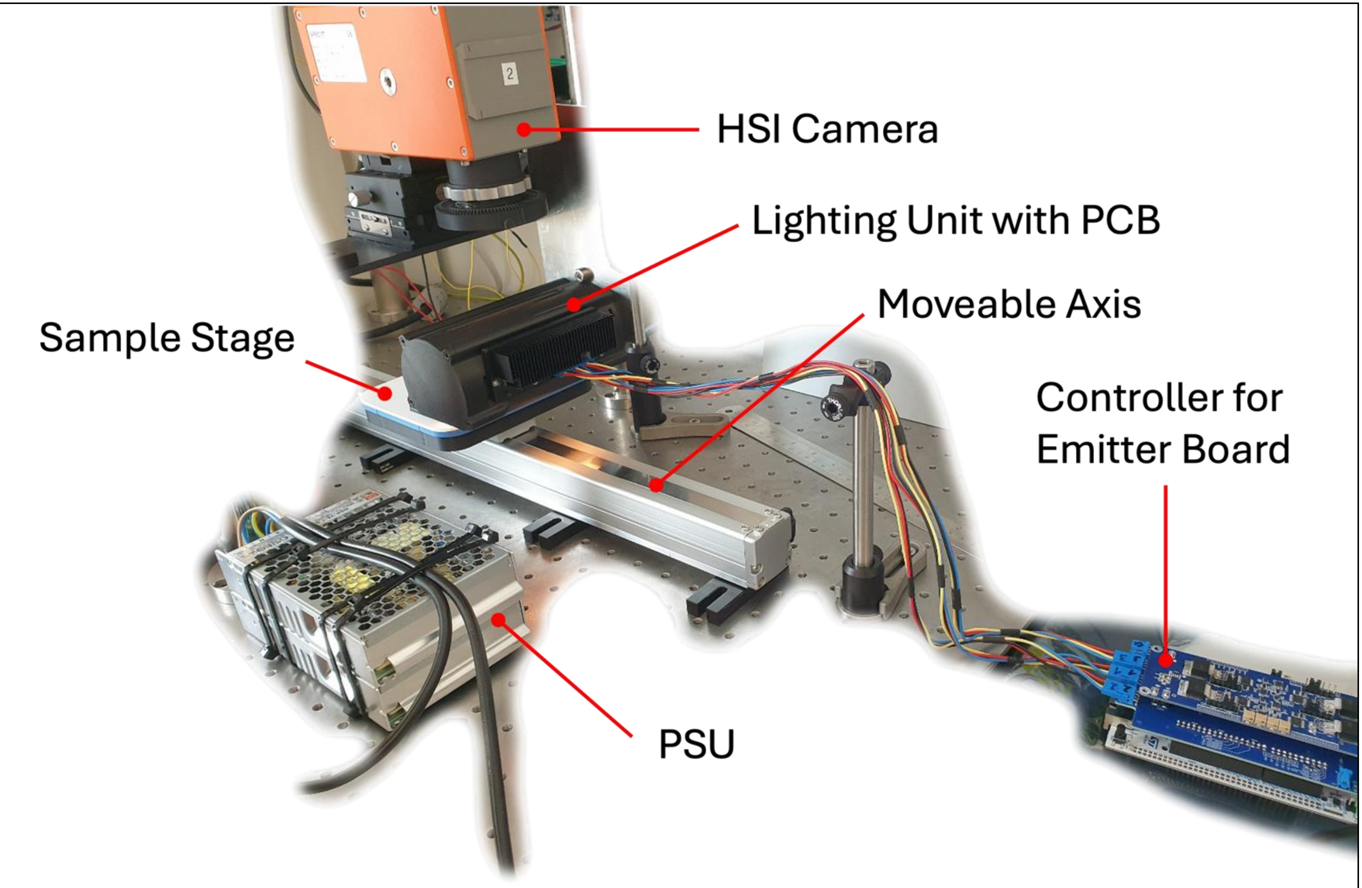
Interior view of the large lighting unit with four emitter boards. The arrangement ensures uniform illumination, and the layout is designed for optimal thermal management and easy integration with the VEpioneer.



Side view of the full lighting unit. Visible components include the beam stop, the entry slit at the top, and the exit slit at the bottom. Cutouts for the emitter boards are located in the base structural tube on the right side. The emitter board assemblies are mounted using a rail system integrated into the housing.

2.5. Test and validation (DIVE)

The small lighting unit (PCB with 48 emitters) was tested as an illumination source for a hyperspectral imaging test setup in combination with a Specim FX17 camera (SWIR). The image below shows the full test setup. For the test setup the PCB in the lighting unit is connected to the controller, which is powered by the PSU. For the planned 300 mm large illumination unit containing 4 PCBs, all the electronic components will be integrated into the demonstrator system. The test setup functions essentially the same as the demonstrator system but is designed for a smaller field of view.



Test setup with small lighting unit containing a single PCB with a total of 48 emitters.

Comparison of the Small Lighting Unit with Conventional Halogen Illumination

The primary objective of the test was to compare how the new emitters performed in contrast to a conventional halogen lamp (the currently used illumination source) under completely identical conditions. Each light source can only be used with its respective diffuser (lamp housing), so the diffuser's influence on sample illumination is inherently combined with that of the light source itself. Tests of the emitters has been carried out at 1.2 V and 1.6 V. Key evaluation criteria included:

- Intensity distribution across the field of view (measured via PTFE reflection spectra at various pixel positions)
- Signal-to-noise ratio (SNR), compared under identical measurement conditions

Additionally, images of a color standard were captured to provide a qualitative visual impression of the illumination under each test condition.

Intensity Distribution

In a hyperspectral push broom setup like used here for testing, a single frame captures spectral information across one spatial line of the scene. Each spatial pixel in that line records a full spectrum of reflected light from a specific point on the sample.

By analysing and comparing the spectra recorded at different spatial pixel positions within the same frame (e.g. positions 1, 160, 320, 480, 640), we can assess how uniformly the illumination is distributed across the field of view.

If the light source is homogeneous and well-diffused, the recorded spectra should be very similar across the spatial positions (especially when imaging a uniform reference target like PTFE). Differences in spectral intensity or shape across the spatial dimension can reveal issues like uneven illumination, hotspots, or wavelength-dependent distribution caused by the light source or its diffuser.

View of the small lighting unit with the PCB in operation at different voltages.
Left: Emitters operated at 1.2 V
Right: Emitters operated at 1.6 V

The emitters were tested at 1.6 V, with integration times of 100 ms. For comparison, a halogen lamp was used with an integration time of 1 ms.

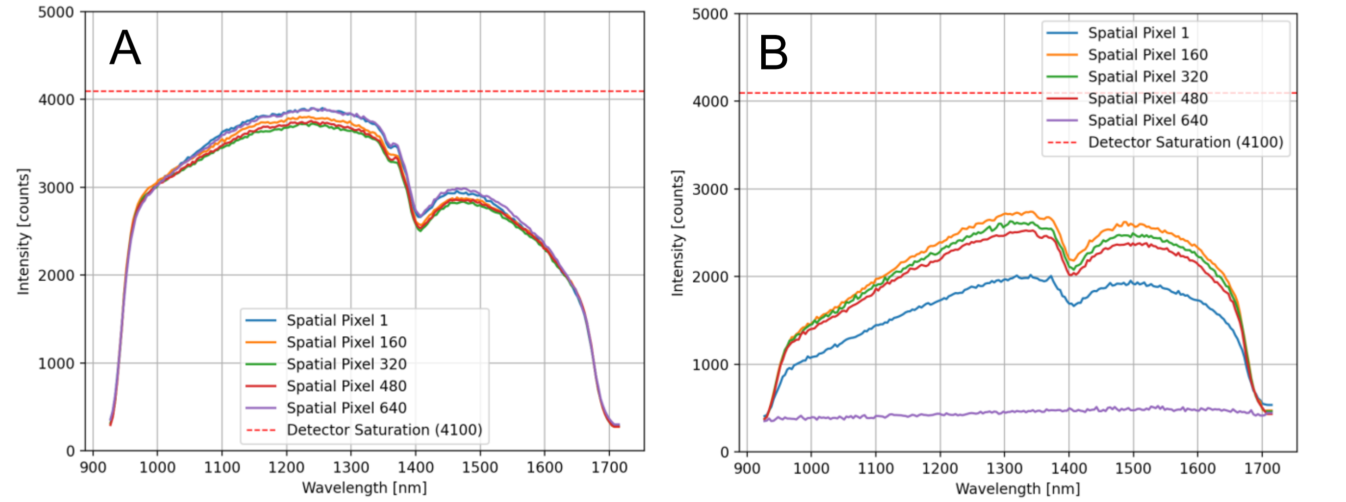
Parameter	Halogen (A)	Emitter 1.6 V – 100ms (B)
Camera angle	3°	
Field of View (FOV)	130 mm	
Pre-gain	1.0	
Integration time	1 ms	100 ms
Frame rate	50 Hz	10 Hz
Distance diffuser to PTFE	4 mm	
Light intensity	100%	1.6 V
Pixel binning	None	
Measurement time	5 minutes after switch-on	

The image shows a single line scan (one frame) acquired by the push broom hyperspectral camera system. Each frame consists of 640 spatial pixels and 224 spectral bands. The marked spatial pixels (1, 160, 320, 480 and 640) represent the reflectance spectrum captured at these positions on a single line of the scene.

Figures A, the resulting signal at the same integration time of 100 ms for the five pixel positions. As can be seen, the light reaching the detector from the emitters is very low (Figure A 100 and B 120 counts) compared to that from the halogen source (Figure C 3600 counts), which reaches around 80% of the detector's saturation level. It is clearly not possible to make reliable measurements under these conditions, which is why the integration time was increased to 100 ms (Figure D) to better compare the intensity distribution across the field of view.

As can be seen in Figure A the fluctuations in the halogen light source across the line scan are very small. The spectra at each pixel position differ only slightly in the infrared region between 1100 nm and 1500 nm, which indicates a very good intensity distribution.

In Figure B, the spectra at pixel positions 1 and especially 640 deviate strongly. This is probably due to misaligned positioning of the diffuser slit relative to the camera and is not a property of the emitter itself. The overall illumination quality can be still assessed at pixels 160, 320, and 480. The differences observed are similar to those seen with the halogen source. Therefore, the overall intensity distribution across the field of view can be considered very homogenous making it a possible illumination option for the demonstrator system. The advantage of the MEMS emitter boards is that each emitter can be controlled so this kind of inhomogeneity can be even further reduced.



The figures A-B show the reflectance spectra at pixel positions 1, 160, 320, 480, and 640 for the different illumination systems. A = Halogen Illumination and Integration time 1 ms, B = Emitters operated at 1.6 V and Integration time 100 ms

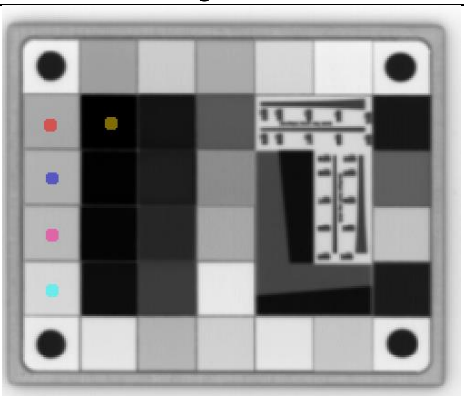
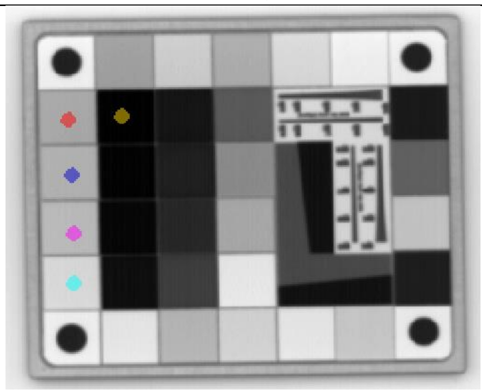
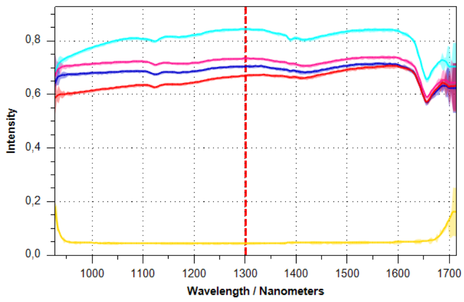
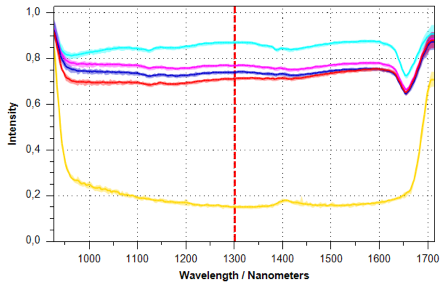
Visual Impression

To assess the performance of the new 4kMEMS emitter in comparison with the conventional halogen lamp, images of a color standard and the corresponding selected spectra were recorded. Additionally, white reference measurements were taken for both light sources under comparable conditions.

The images of the color standard reveal that the general color rendering and spatial uniformity are preserved with the 4kMEMS emitter, although slight differences in brightness and color intensity are visible, particularly in the shorter wavelength range.

The selected spectra confirm this observation, showing slightly lower intensity and minor spectral variation with the new emitter, especially at the edges of the spectral range. However, these differences remain within acceptable limits for most application scenarios.

White reference measurements highlight the spectral distribution and homogeneity of both sources. While the halogen lamp provides a more uniform spectrum across the VNIR range, the 4kMEMS emitter demonstrates sufficient stability and repeatability, indicating its potential for practical use.

<table>
<tr><th>Halogen - 1 ms</th><th>4kMEMS Emitter @1.6V - 100 ms</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Monochrome Image @1300 nm</td><td>Monochrome Image @1300 nm</td></tr>
<tr><td>
</td><td>
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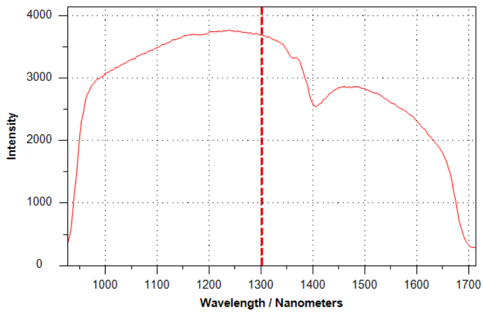
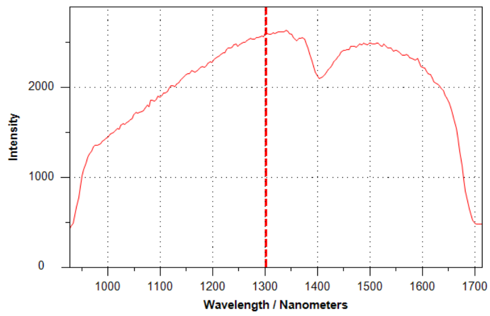
<tr><td>Selected Spectra on the Color Standard</td><td>Selected Spectra on the Color Standard</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>White Reference PTFE</td><td>White Reference PTFE</td></tr>
</table>

3. Conclusions

- We developed wafer scale technology to make emitters that could be mounted directly on PCBs after dicing.
- Electronics to drive large arrays of emitters was designed, built and implemented.
- A diffusive lamp housing specifically for the SWIR emitters was designed, built and tested.
- PCBs compatible with lamp housing and the drive electronics were design built and installed in to the lamps.
- The designs and electronics were completed for full lamps
- The complete systems using Small lamps were built and tested.
- We made a preliminary evaluation of a Small Lamp although the light output is lower than for a tungsten lamp the signal levels are adequate – in particular the ability of the emitters to operate in a vacuum environment is a significant advantage in certain environments,
- The special uniformity of the tested lamp is adequate – future tests can include controlling the individual emitters in order to improve this.
- Next steps: Move to larger lamps and test aspects such as lifetime, improved spectral and spatial uniformity

4. Degree of Progress

Degree of fulfilment of the task activities respect of what reported in the DoA.

The deliverable specifications was clearly to demonstrate 4 lamps with more than 80 emitters.
We have only been able to produce 4 lamps with 48 emitters of which one was evaluated. This has been due to a supply issue on the foundries making the emitters and not due to intrinsic limits.

Going forward, the intention is to improve the supply of emitters so that lamps of a larger size (192 emitters 40 cm illumination length) can be made.

Regarding the main technological goals of this deliverable—namely, the implementation of target manufacturing processes at the wafer scale, the realization of corresponding multichannel driver circuits, and the implementation of a diffuse multi-emitter light source—this has been achieved.

All technical obstacles were resolved during the research and development campaign. The design of the use-case-embedded light source has also been finalized.

Based on these achievements, we consider this deliverable to be 100% fulfilled. The remaining light sources will be delivered in the coming months and documented in the corresponding technical report.

5. Dissemination Level

Public