EEE24003 Development of a Platform for Low Intensity Light Detection Used for Optical Analysis of Water Purity

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Abstract - Ensuring sustainable water resources is vital for Singapore, where reliable water quality monitoring supports safe and efficient treatment processes. In collaboration with the Nanyang Environment & Water Research Institute (NEWRI), this research presents a miniaturized optical detection platform as a proof-of-concept alternative to conventional UV/fluorescence-based water monitoring systems. It aims to perform rapid and efficient monitoring of water desalination and purification processes, with additional potential applications for the analysis of biological or biochemistry samples.

The developed system integrates both optical and electrical parts to measure fluorescence and UV absorbance parameters as indicators of water quality. The optical part of the system features an elliptical reflective cavity to enhance weak fluorescence signal collection, combined with cylindrical lenses, beam splitters, and long-pass filters to optimize excitation and UV absorbance/ transmission (UVA/T) detection pathways. Iterative ZEMAX simulations were performed to determine optimal configurations for the optical pathways, the lens parameters and irradiance distributions. The electrical system design comprises transimpedance amplifiers, lock-in amplifiers and other necessary power and control systems to perform low light-intensity detection and signal processing.

Through systematic and iterative simulations, this research evaluates various optical assemblies and validates an optimized setup of optical and electrical systems that focuses on deployable and practical applications. Further refinement of the prototype and system integration will be explored in future work to advance toward robust field implementation.

Keywords - Low-intensity light detection, Fluorescence, UV absorbance, Elliptical cavity, ZEMAX, Lock-in amplifier, Water purity analysis, Optical system design

1 INTRODUCTION

Ensuring a safe and sustainable water supply is a strategic priority for Singapore, where robust, real-time water quality monitoring systems are essential to maintain the resilience of water treatment infrastructure and desalination plants.

Optical methods offer a promising alternative for water quality monitoring. Key benefits include non-destructive, pollution-free and multi-parameter detection while remaining highly adaptable to miniaturization and rapid, on-site deployment. Optical methods also allow instant measurements without the need to extract the water samples, which shows potential for continuous real-time monitoring. Additionally, our investigated methods are label-less, as no reagents are added for the testing.

In particular, analysis of the **fluorescence** of undesired elements that may be present in the sample has emerged as a powerful technique to identify trace organic contaminants by leveraging characteristic excitation-emission matrix (EEM) peaks. At the same time, **UV absorbance/ transmission (UVA/T)** complements fluorescence measurements by enabling quantitative analysis of other non-fluorescent dissolved pollutants, thus allowing cross-validation for a more robust water quality assessment. However, the existing equipment that can perform UVA/T and fluorescence measurements is typically large, bulky and expensive, requires highly qualified personnel to operate, and is not in real time. All these significant disadvantages make widespread deployment and/or easy and fast real-time water assessment challenging.

Therefore, this research aims to develop the primary concept for a miniaturized and reliable optical detection platform as a proof-of-concept alternative to conventional UVA/T and fluorescence-based water monitoring system. Specifically, this work was part of a larger project that focused on detecting the degradation of the membranes used in water purification systems. For this purpose, 3 wavelengths are of interest, but in our work we used only one of the key wavelengths identified by NEWRI, namely 395 nm, which leads to characteristic UVA and fluorescence excitation of certain contaminants of interest in water samples.

2 OPTICAL SYSTEM DESIGN

Our proposed optical water purity detection platform shown in Fig.1 aims to detect and measure two key parameters of interest: UV excitation light absorbance/transmission in/through the sample (UVA/T), as well as the inherent fluorescence (FLU) that it also causes (IF any contaminants are still present in the sample). The optical system is designed to address both aspects through carefully structured light paths, enabling the following:

- Efficient illumination of the sample with the excitation light from a light source, preferably of high intensity and which should be focused onto the water sample;
- Effective collection of (ideally ALL) the weak fluorescence light emitted by the water sample;
- Detection of excitation light transmitted through the water sample;
- Acquisition of a reference signal split out from the same excitation light source for subsequent for UVA/T measurement signal processing;
- Employ a signal detection and processing method suitable to extract weak signals and compensate for light source fluctuations. Specifically, in our case we employed the lock-in method.

For the main project purpose of detecting the degradation of the membranes used in water purification systems, NEWRI identified 3 wavelengths of interest. However, for simplicity, in our work we used only the wavelength of 395 nm.

2.1 OVERALL OPTICAL SYSTEM STRUCTURE

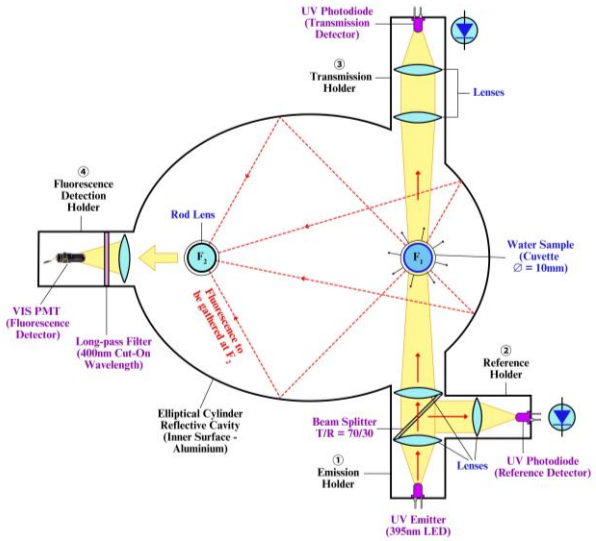


Figure 1. 2D Schematic Representation of our Proposed Optical System

The proposed optical system is composed of 5 main components:

1. Main body, i.e. elliptical cylinder reflective cavity
2. Light emission holder
3. Reference detection holder
4. Transmission/Absorption detection holder
5. Fluorescence Detection Holder

2.1.1 Main Body – Elliptical Cylinder Reflective Cavity

Since the fluorescence signal emitted by the water sample is extremely weak, it is essential to employ a structure that can maximize the capture of all emitted fluorescence light. Therefore, we proposed using an elliptical cylinder reflective cavity, due to the unique optical properties of an ellipse: **any** ray emitted from one focal point will, upon reflecting off the inner elliptical surface, ultimately reach and pass through the second focal point. Leveraging this principle, the cuvette containing the water sample is positioned at the first focal point (F_1) of the elliptical cavity, so that its isotropically emitted fluorescence can (ideally) be all concentrated at the second focal point (F_2) where a series of detection optics can be employed. To further enhance the reflectivity, the internal surface of the cavity can be made of, or coated with, aluminium.

2.1.2 Emission Holder

The emission holder is designed to ensure the efficient illumination of the excitation light from a light source onto the water sample -in a cuvette, in our case- to induce fluorescence.

In this emission holder, **UV LEDs (model LZ1-00UBN0 from OSRAM)** with a peak emission wavelength of 395 nm and an average power of 1.2 W were used to make up the light source. This LED type was chosen based on a holistic evaluation of factors such as high output power, narrow beam divergence and cost-effectiveness, etc. The emitted light is split with a beam-splitter **beam splitter (Edmund Optics 30R/70T 25 x 25mm, UV Plate Beamsplitter #48-197)**, and 70% of it is transmitted to 2 **cylindrical lenses** that then focus it onto the sample. The remaining 30% of the initial excitation light beam is diverted toward the reference holder. This specific ratio prioritizes delivering sufficient light power to the sample for optimal fluorescence excitation, while still maintaining enough signal to establish an accurate reference measurement which is necessary for the subsequent UVA/T detection measurement.

2.1.3 Reference Holder

Within the reference holder, a **cylindrical lens** focuses the portion of the excitation beam diverted by the beam splitter onto the **reference**

photodiodes (PDs) located at the end of the holder. For simplicity, due to the great difficulties in finding a dedicated UV detector, we came up with the original idea to use as photodiodes the same type of LEDs (LZ1-00UBN0) used in the emission holder. This ensures optimal sensitivity and compatibility in detecting the same emitted wavelength.

These reference photodiodes will convert the detected light into a photocurrent that reflects real-time variations in the intensity of the excitation light source. This reference signal is essential for the subsequent weak signal lock-in detection method, which compares the measured weak signals and the reference signal to effectively extract the UV absorbance information. In short, this reference signal improves measurement reliability and accuracy as it allows compensation for instability and fluctuations in the light source, while providing the baseline with respect to which the amount of light absorbed in the sample can be deduced accurately.

2.1.4 Transmission Holder

The transmission holder receives the part of the excitation light beam that has passed through the water sample. This holder enables quantitative measurement of the UV absorbance parameter, since the attenuation of light can reflect the concentration of such UV-absorbing compounds in the water sample based on the Beer-Lambert's Law.

Within this transmission holder, another set of **cylindrical lenses** is employed to focus the transmitted light beam onto the **photodiodes** positioned at the end of the holder. Similarly, again LEDs of the same type as those used for emission were employed here as well as photodiodes to ensure consistent detection performance. The detected signal is subsequently processed in conjunction with the reference signal to determine quantitatively the absorption parameter.

2.1.5 Fluorescence Detection Holder

The fluorescence detection holder enables the quantitative measurement of fluorescence (FLU) parameter. Since the excitation UV stray light can cause interference and lead to inaccuracy if it reaches the fluorescence detector, it is essential to block stray excitation light from entering his holder. A **long-pass optical filter** with a 400 nm cut-on wavelength is therefore incorporated within the holder to block the excitation light while allowing only the fluorescence (visible light range) emitted by the excited water sample to pass through.

The fluorescence light, collected at the second focal point (F_2) of the elliptical reflective cavity, is directed through additional optical elements and channelled to the **photomultiplier tube (PMT) (Hamamatsu H11642-011)** inside the holder via pyramidal funnel. The PMT, with its extremely high sensitivity and low noise characteristics, is well-suited to detect the very weak fluorescence signals. The output signal from the PMT is then processed together with the reference signal, enabling accurate extraction of the FLU parameter using the lock-in detection method.

In summary, the overall optical system integrates a main body of the elliptical reflective cavity and supporting holders to effectively deliver, guide, and detect both fluorescence and UV absorbance signals. The following sections present the results of ZEMAX optical simulations that evaluated the performance of the proposed optical structure and allowed us to deduce the optimal lens parameters necessary to achieve the desired detection objectives.

2.2 FLUORESCENCE CAPTURING PERFORMANCE OF THE ELLIPTICAL CYLINDER REFLECTIVE CAVITY

Optical simulations were conducted using ZEMAX OpticStudio for two main purposes. First, we had to evaluate whether the main optical structure of elliptical cylinder reflective cavity can effectively capture fluorescence emissions at the second focal point (F_2). Second, we had to deduce the number, type and characteristics of the lenses that needed to be used in various parts of our optical setup.

For the first purpose, the elliptical cavity was first modelled with the exact design dimensions in SolidWorks, then the 3D model is imported to ZEMAX OpticStudio incorporating the relevant reflective properties of an aluminium-coated internal surface. This ensures that the imported 3D model would realistically represent the reflection and absorption behaviour expected in the actual prototype.

In ZEMAX, Ray Trace and Irradiance Map analysis were used to simulate and visualize the distribution of fluorescence light. The simulation was conducted by placing a cylindrical isotropic light source at the first focal point (F_1) of the elliptical cavity to replicate the fluorescence emitted from the water sample. At the second focal point (F_2), a rectangular ZEMAX "detector" 70 mm × 110 mm in size was defined and set to capture and quantify the intensity of light collected at F_2 as shown in Fig.2-a. An irradiance map obtained from the ray tracing simulation showed a clear, prominent high-irradiance strip centered on the "detector", as it can be seen in Fig.2-b. This pattern shows that the elliptical cavity successfully concentrates in F_2 the isotropic fluorescence light emitted at F_1. These results confirm that the elliptical cylinder reflective cavity demonstrates excellent fluorescence collection performance. The theoretical optical

principle is validated, and this design is ideal to be used for the system.

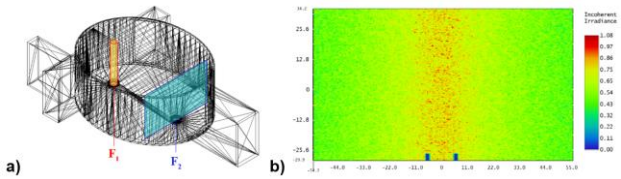


Figure 2: a) ZEMAX detector for FLU light (blue plane); b) Irradiance map of FLU light arriving at the 2nd focal point of the reflector

2.3 EMISSION HOLDER DESIGN – MAXIMISING UV IRRADIANCE ONTO WATER SAMPLE

The emission holder houses several components including emission LEDs, a beam splitter and cylindrical convex lenses. Its primary function is to deliver the excitation light efficiently from the light source onto the water sample in a cuvette placed in F1, thereby inducing fluorescence. Hence, a key purpose of the emission holder design is to maximize the irradiance of the excitation light onto the water sample to ensure the emission of the strongest possible fluorescence light. The cylindrical cuvette used in this project has a cross-sectional diameter is 10 mm, which sets an important geometric constraint for focusing performance.

To optimize light delivery, three types of lens configurations and light emitters with different number of LEDs were proposed and evaluated through iterative ZEMAX optical simulations. In all cases, rod lenses were used to collimate the excitation light and focus it, so as to uniformly illuminate most of the cuvette's cross-section. The simulated configurations included:

- **Version 1A**: 1 Rod Lens with 2 rows of 5 LEDs
- **Version 1B**: 1 Rod Lens with 1 row of 10 LEDs

- **Version 2A**: 2 Rod Lenses with 2 rows of 5 LEDs
- **Version 2B**: 2 Rod Lenses with 1 row of 10 LEDs

- **Version 3A**: 2 Cylindrical Convex Lenses with 2 rows of 5 LEDs

- **Version 3B**: 2 Cylindrical Convex Lenses with 1 row of 10 LEDs

- **Version 4**: 2 Cylindrical Convex Lenses with 1 row of 10 LEDs (Optimization from Version 3B)

- **Version 5**: Control Set without any Lenses with 1 row of 10 LEDs

All simulation scenarios were done with 395 nm UV LEDs (each with a power of 1.2W), a beam-splitter (25 mm × 25mm) and five "detectors" (each with a size of 12 mm × 70 mm) defined in ZEMAX and placed at different locations to measure light power distribution along the following points of the emission and transmission paths:

- **Detector 1**: Emission LEDs
- **Detector 2**: Emission Holder Slit
- **Detector 3**: Water Sample
- **Detector 4**: Transmission Holder Slit
- **Detector 5**: Transmission Photodiodes

For each version, the percentage of total power received at each "detector" location was also calculated relative to the initial emission power measured at "Detector" 1. Of most interest was "Detector" 3 and "Detector" 5 as they are critical for evaluating FLU and UVA light propagation, focusing and detection performance.

2.3.1 Version 1A: 1 Rod Lens with 2 Rows of 5 LEDs

The simulation results of Version 1A depicted in Fig.3 are summarized in Table 1.

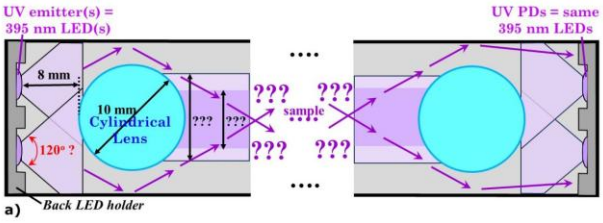


Figure 3. Top view of Version 1A

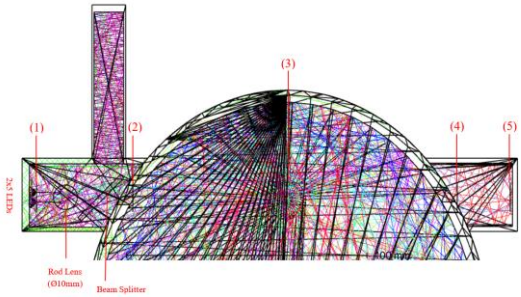
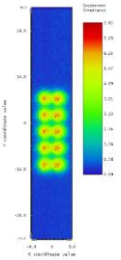


Figure 4. "Detector" locations in ZEMAX simulation

	Detectors	Total Power (W)
(1) Emission LEDs		10.6980 (100%)

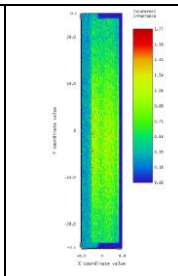
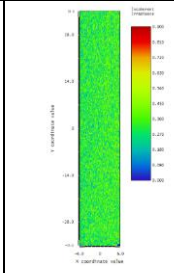
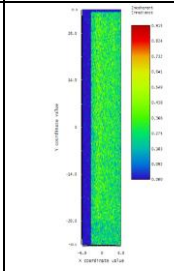
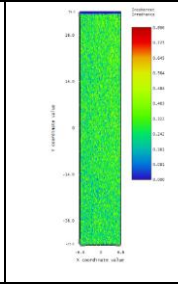
(2) Emission Holder Slit		4.4500
(3) Water Sample		2.7305 (25.52%)
(4) Transmission Holder Slit		1.9296
(5) Transmission Photodiodes		2.3395

Table 1. Irradiance maps and total power received by all "detectors" in Version 1A

2.3.2 Version 1B: 1 Rod Lens with 1 Row of 10 LEDs

In Version 1B, the two rows of LEDs of Version 1A are replaced with a single row. This modification was based on the hypothesis that having one row would better align the light along the principal axis and create a more orderly light path.

The simulation results of Version 1B, which is illustrated in Fig.5, are summarized in Table 2, showing slight improvements compared to Version 1A.

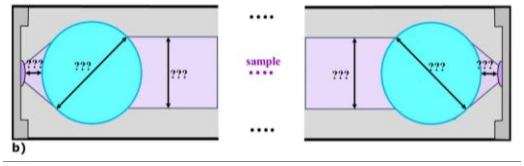


Figure 5. Top view of Version 1B

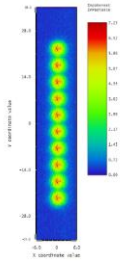
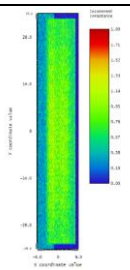
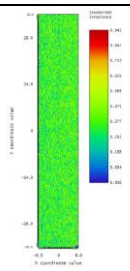
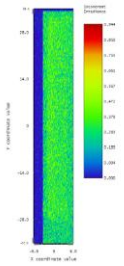
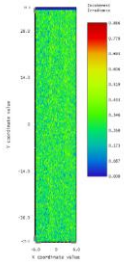
	Detectors	Total Power (W)
(1) Emission LEDs		10.3350 (100%)
(2) Emission Holder Slit		4.9643
(3) Water Sample		3.0524 (29.53%)
(4) Transmission Holder Slit		2.0262
(5) Transmission Photodiodes		2.4648

Table 2. Irradiance maps and total power received by all "detectors" in Version 1B

2.3.3 Version 2A: 2 Rod Lenses with 2 Rows of 5 LEDs

In Version 2A, the emission holder was configured with two rod lens and two rows of five LEDs. Here, the first rod lens collimates the divergent excitation light, while the second rod lens focuses the resulting parallel light beam onto the cuvette. The

simulation results of Version 2A are summarized in Table 3.

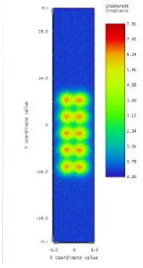
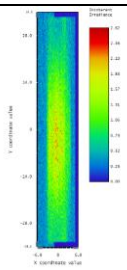
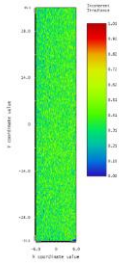
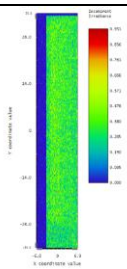
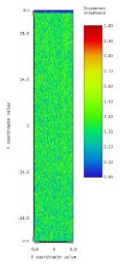
	Detectors	Total Power (W)
(1) Emission LEDs		10.8100 (100%)
(2) Emission Holder Slit		5.7713
(3) Water Sample		3.1496 (29.14%)
(4) Transmission Holder Slit		2.2209
(5) Transmission Photodiodes		2.6929

Table 3. Irradiance maps and total power received by all "detectors" in Version 2A

2.3.4 Version 2B: 2 Rod Lenses with 1 Row of 10 LEDs

In Version 2B, the configuration from Version 2A was modified by replacing the two rows of five LEDs with a single row. Similar to Version 1B, the focusing performance improves when using single row of LEDs. The simulation results of Version 2B are summarized in Table 4.

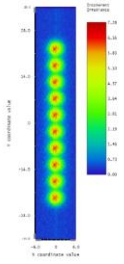
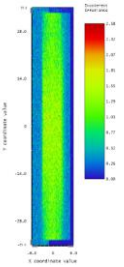
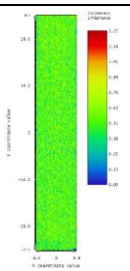
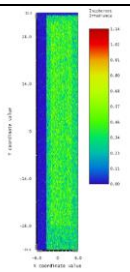
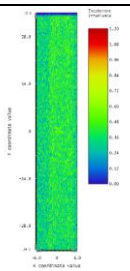
	Detectors	Total Power (W)
(1) Emission LEDs		10.6290 (100%)
(2) Emission Holder Slit		5.8965
(3) Water Sample		4.4750 (42.10%)
(4) Transmission Holder Slit		2.4888
(5) Transmission Photodiodes		3.0321

Table 4. Irradiance maps and total power received by all "detectors" in Version 2B

2.3.5 Version 3A: 2 Cylindrical Convex Lenses with 2 Rows of 5 LEDs

For Version 3A and 3B, we explored an assembly of cylindrical convex lenses (see Fig.6) as an

alternative to rod lenses. As seen in Fig.6, a beam splitter can also be placed between the two lenses to redirect part of the collimated light beam to a perpendicularly placed reference holder (not shown in Fig.6), where the light remains collimated as well.

A systematic optimization approach was implemented in ZEMAX to achieve maximum UV irradiance on the water sample. The final optimal two-lens combination, shown in Table 5, was determined by using the first convex lens to collimate the divergent excitation light into a parallel beam and the second convex lens to focus the collimated beam onto the water sample, thereby illuminating the largest cross-sectional area of the water sample to maximize fluorescence excitation within it.

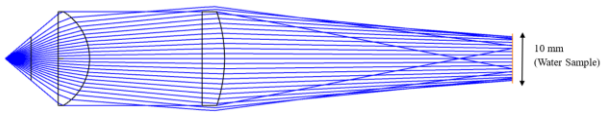
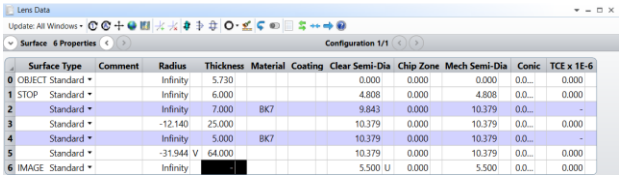


Figure 6. Assembly of 2 convex lenses for collimation and focusing of excitation light onto the sample

The simulation results of Version 3A are summarized in Table 6.



	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard	Infinity	5.730			0.000	0.000	0.000	0.0...	0.000
1	STOP	Standard	Infinity	6.000			4.808	0.000	4.808	0.0...	0.000
2		Standard	Infinity	7.000	BK7		9.843	0.000	10.379	0.0...	-
3		Standard	-12.140	25.000			10.379	0.000	10.379	0.0...	0.000
4		Standard	Infinity	5.000	BK7		10.379	0.000	10.379	0.0...	-
5		Standard	-31.944 V	64.000			10.379	0.000	10.379	0.0...	0.000
6	IMAGE	Standard	Infinity				5.500 U	0.000	5.500	0.0...	0.000

Table 5. Lens data resulted from ZEMAX simulations for Version 3A

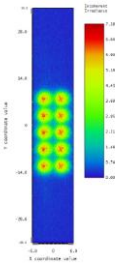
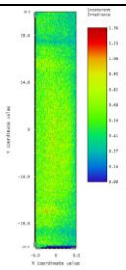
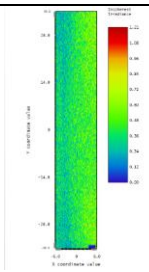
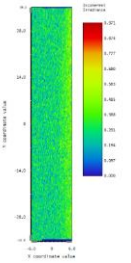
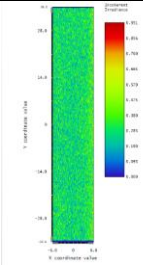
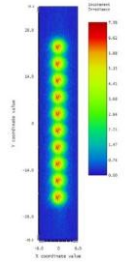
	Detectors	Total Power (W)
(1) Emission LEDs		9.9871 (100%)
(2) Emission Holder Slit		4.7161
(3) Water Sample		3.3823 (33.87%)
(4) Transmission Holder Slit		2.5026
(5) Transmission Photodiodes		2.3739

Table 6. Irradiance maps and total power received by all "detectors" in Version 3A

We can see in Table 6 that in Version 3A "Detector" 3 has a low irradiance along a vertical central line, indicating that the light is not focusing and illuminating the water sample as desired. This discrepancy may be caused by using two rows of five LEDs, which could be misaligned with respect to the principal axis. To address this issue, Version 3B was considered, replacing the two rows with a single row of ten LEDs.

2.3.6 Version 3B: 2 Cylindrical Convex Lenses with 1 Row of 10 LEDs

The simulation results of Version 3B are summarized in Table 7.

	Detectors	Total Power (W)
(1) Emission LEDs		10.1290 (100%)

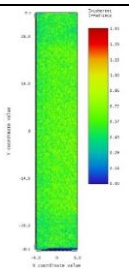
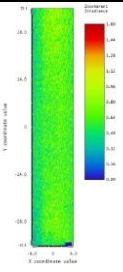
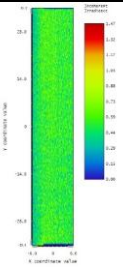
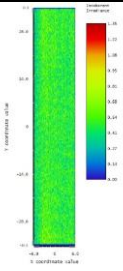
(2) Emission Holder Slit		4.7962
(3) Water Sample		5.2309 (51.64%)
(4) Transmission Holder Slit		4.2985
(5) Transmission Photodiodes		3.9797

Table 7. Irradiance maps and total power received by all "detectors" in Version 3B

The data in Table 7 show that the focusing performance improved significantly in Version 3B compared to 3A, with the total power detected by "Detector" 3 increasing from 33.87% to 51.64%, after switching to using a single row of ten LEDs. This improvement is attributed to better alignment along the principal axis. As a result, Version 3B was selected for further optimization. Specifically, to evaluate the focusing performance on greater detail, we additionally analysed Version 3B, but now without the reflective cavity. A large 35 mm × 35 mm ZEMAX "detector" was defined as placed at the water sample location, and ray tracing was performed to characterize the irradiance distribution. The simulated setup is shown in Fig.7, which clearly shows that effective focusing performance was observed for Version 3B using a single row of ten LEDs.

Given the cuvette's 10 mm diameter, most of the excitation light successfully illuminated the cross-section of the water sample. However, part of light still fell outside the target area of cuvette's cross-sectional area and did not contribute to the illumination onto the water sample. To address this, Version 4 introduced further optimization by increasing the radius of curvature of the second convex lens. This adjustment ensured that the strip of excitation light had a width that matched the 10 mm width of the cuvette, thereby maximizing illumination of the water sample.

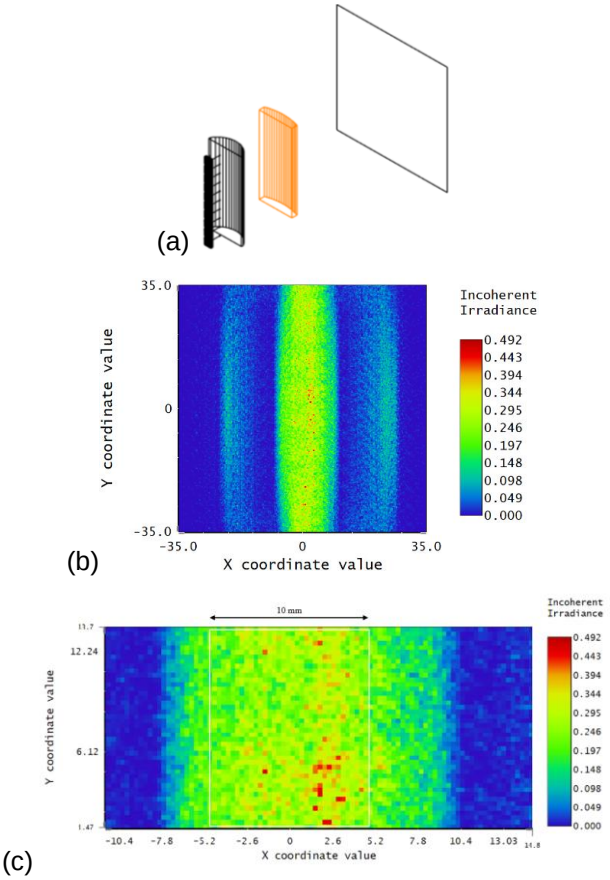


Figure 7: Further analysis of Version 3B focusing performance: a) Modified setup without reflecting cavity; b) Resulting irradiance map at the "detector"; c) Irradiance map with the labelled cuvette's cross-section

2.3.7 Version 4: 2 Cylindrical Convex Lenses with 1 Row of 10 LEDs (After Optimization from Version 3B)

Further optimization of Version 3A led to the development of Version 4. using iterative simulations by fine-tuning and increasing the radius of curvature of the second convex lens to achieve the highest UV irradiance power at "Detector" 3 corresponding to the water sample. As shown in Table 8, the final results show an improvement from 51.64% to 57.54%.

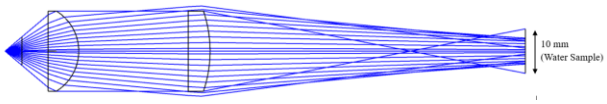


Figure 8. Optimized assembly of 2 convex lenses for collimation and focusing of excitation light resulted after ZEMAX simulations that refined and optimized the setup of Version 3B

Lens Data

Update: All Windows | Surface 6 Properties | Configuration 1/1

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Par 0(unuse
0	OBJECT Standard		Infinity	3.814			0.000	0.000	0.000	0.0...	0.000	
1	STOP Standard		Infinity	6.000			3.200	0.000	3.200	0.0...	0.000	
2	Toroidal		Infinity	7.000	N-BK7		8.235	-	-	0.0...	-	0
3	Toroidal		-10.648	25.000			9.103	-	-	0.0...	0.000	0
4	Toroidal		Infinity	5.000	N-BK7		9.103	-	-	0.0...	-	0
5	Toroidal		-28.000 V	72.000			9.103	-	-	0.0...	0.000	0
6	IMAGE Standard		Infinity	-			4.500 U	0.000	4.500	0.0...	0.000	

Table 8. Lens data resulted from ZEMAX simulations for Version 4

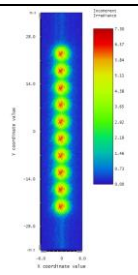
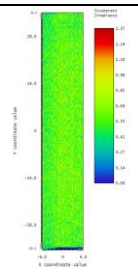
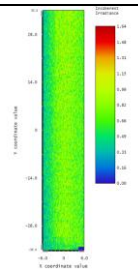
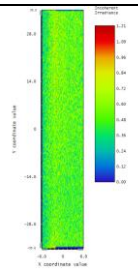
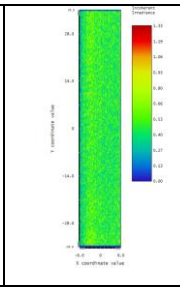
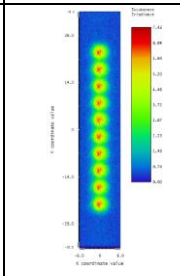
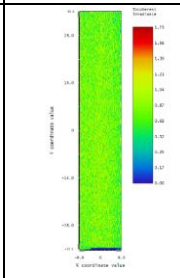
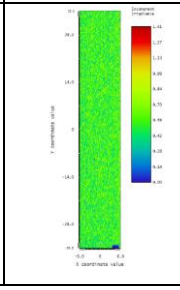
	Detectors	Total Power (W)
(1) Emission LEDs		9.9879 (100%)
(2) Emission Holder Slit		4.9360
(3) Water Sample		5.7470 (57.54%)
(4) Transmission Holder Slit		4.1993
(5) Transmission Photodiodes		3.8277

Table 9. Irradiance maps and total power received by all "detectors" in Version 4

2.3.8 Version 5: Control Set without any Lenses with 1 Row of 10 LEDs

Version 5 is a control set without any lenses with a single row of ten LEDs. After comparison with Version 5, it was found that the irradiance power onto the water sample improved from 40% (in the control set) to 57.54% with the use of the two cylindrical convex lenses in Version 4. Therefore, Version 4 featuring the optimized two cylindrical convex lenses, was ultimately selected for implementation.

	Detectors	Total Power (W)
(1) Emission LEDs		11.484 (100%)
(2) Emission Holder Slit		6.7681
(3) Water Sample		4.5936 (40%)

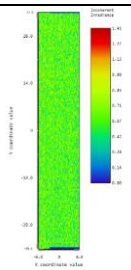
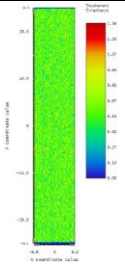
(4) Transmission Holder Slit		4.9811
(5) Transmission Photodiodes		4.8360

Table 10. Irradiance maps and total power received by all "detectors" in Version 5

2.4 UVA/T HOLDER DESIGN

The same lens assembly of Version 4 was applied to both the emission and transmission holders in a symmetrical configuration. This design approach was based on the assumption that the effects of scattering and refraction within the water sample are negligible, making the optical path through the transmission holder optically reversible in symmetry relative to the central point of the sample. This simplification allows for the use of two identical lens assemblies, offering a cost-effective and convenient solution by avoiding the need to design and procure separate lens sets specifically for the emission and absorption/transmission detection holder, respectively. As illustrated in Fig.9, the designed structure of the lens set in the UVA/T holder is a symmetrically reversed version of the one used in the emission holder.

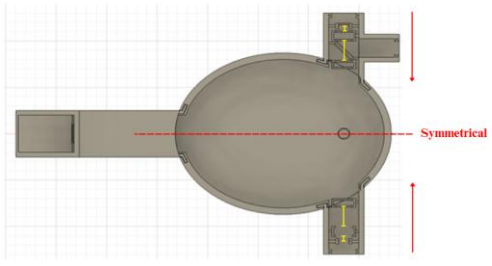


Figure 9. Symmetrical lens design of emission and UVA/T measurement holders

2.5 REFERENCE HOLDER DESIGN

Assuming that the incident light reflected by the beam splitter toward the reference holder is also collimated, it is feasible to utilize the same first cylindrical convex lens from Version 4, as used in the emission holder, to focus the light onto the end of the reference holder where the reference photodiodes are located. This is valid provided that the distance from the lens to the end of the reference holder is identical to that in the emission holder, given that the lenses share identical focal lengths and focusing characteristics. This arrangement is also practical and cost-effective, allowing the system to standardize around just two types of plano-convex cylindrical lenses across the three holders of emission, reference and transmission.

As shown in Fig.10-b, the prominent vertical strip of light demonstrates that the same first cylindrical convex lens used in the emission holder can also effectively focus the light onto the end of the reference holder.

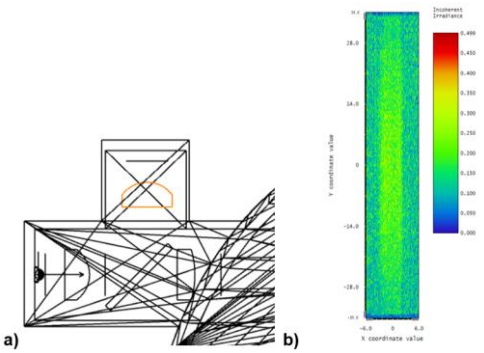


Figure 10. a) Top view of the reference holder. Notice the diagonally placed beam-splitter in the middle of the holder; b) Irradiance map of a ZEMAX "detector" defined and placed at the end of the reference holder (i.e. at the input slit into the elliptical reflector)

2.6 FLUORESCENCE DETECTION HOLDER DESIGN

For the fluorescence detection holder, a rod lens was initially proposed to be positioned at the second focal point (F_2) of the elliptical reflective cavity. Its function is to collimate the fluorescence (FLU) light reflected from the elliptical surface after being emitted isotropically from the UV-illuminated water sample located at the first focal point (F_1).

Fig.11 shows the results of ZEMAX simulations which demonstrate that using this rod lens placed in F_1, at least theoretically, part of the FLU light received in F_2 can be effectively directed toward the fluorescence detection holder.

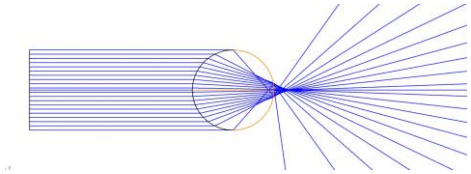


Figure 11. ZEMAX simulations results for FLU light collimation with a rod lens placed at F_2

However, in the current prototype version, no rod lens system was incorporated – mainly because subsequent mor detailed raytracing ZEMAX simulations could not confirm that such collimation can indeed occur with good efficiency. For simplicity, a pyramidal funnel was adopted instead (see Fig.12). It would constrain and "focus" the free-space propagation of FLU light by physically directing via multiple reflections it toward the effective input area of the PMT detecting window. This enabled a quick solution that would still allow collection of the weak FLU light with acceptable efficiency while keeping the design practical, cheaper and easier to fabricate. Future prototypes should resume ZEMAX simulations to deduce systematically a (more efficient) lens system that could further improve the performance.

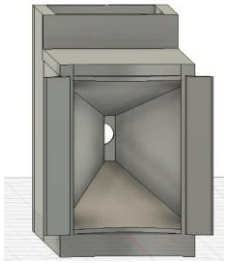


Figure 12. Pyramidal funnel directing FLU light toward the PMT in the FLU detection holder

3 DESIGN OF THE ENTIRE 3D STRUCTURE

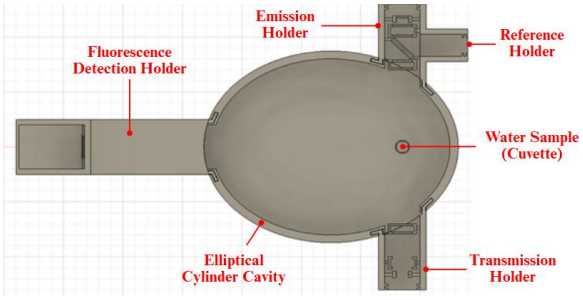


Figure 13. Top view of the entire system design and its adjacent holder

The 3D modelling of the entire system's structure (shown in Fig.13) was performed using two CAD softwares: SolidWorks and Autodesk Fusion 360. The 3D modelling was organized into 4 detachable substructures for realization by 3D printing and subsequent easy assembly:

1.Main body, i.e. elliptical cylinder reflective cavity;

2.Emission holder together with reference holder (Fig.14-a);

3.Transmission holder (Fig. 14-b);

4. Fluorescence detection holder (Fig. 14-c);

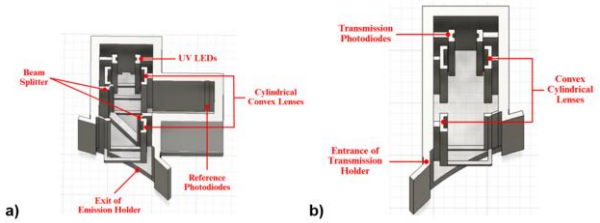


Figure 14. 3D designs of the: a) Emission & reference holder; b) Transmission holder

These mechanical structures were designed to house critical optical and detection components in precise alignment, including photodiodes, emission LEDs, cuvette, beam splitter and cylindrical lenses. Therefore, the internal features of the holders, such as slots, recesses, and mounting channels, were dimensioned carefully based on the optimal parameters and specifications obtained in the previous optical simulations. For example, critical parameters (lens thickness, inter-lens spacing, distances to beam splitter, and overall holder lengths) were accurately replicated from ZEMAX simulation data to ensure that the physical prototype will have the intended light path and focusing performance as simulated.

For the FLU light detection holder, however, the current prototype version does not yet incorporate an additional lenses system. As explained in previous sub-section 2.7, the current version of design adopts a pyramidal funnel to constrain and direct the captured FLU light toward the effective detection area of the PMT.

The mechanical strength of the design was another key consideration. The main cavity and external walls of the holders were designed with a thickness of 5 mm to provide robust support, while interior structural features that directly house optical or electronic components were reduced to a thickness of 2.5 mm to maintain practical clearances.

A detachable top cover was integrated to facilitate easy access to the cuvette for sample handling. This allows the cuvette to be conveniently removed, emptied, refilled and reinstalled in its precise position at the first focal point of the elliptical cavity.

A critical design consideration was also to ensure each holder could be conveniently attached and detached from the main elliptical cavity structure. A top-bottom slide-in mechanism was adopted after

several prototype iterations to ensure a precise and secure fit. The final assembly of the holders with the main structure is shown in Fig.16.

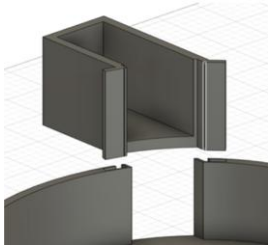


Figure 15. Top-bottom slide-in mechanism of the holders onto the elliptical reflector

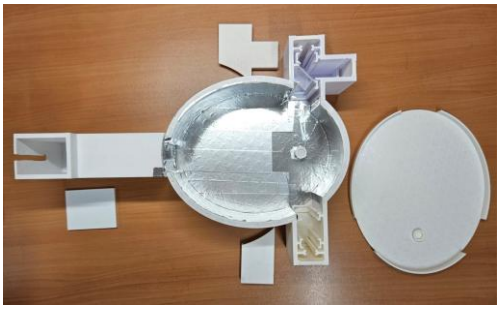


Figure 16. Final assembly of the entire mechanical structure of the system

4 CONCLUSION

This research project has made significant progress toward developing a macroscopic proof-of-concept optical detection platform integrating fluorescence and UV absorbance measurements for water quality assessment. The work involved designing an elliptical reflective cavity to enhance weak fluorescence signal collection, supported by carefully modelled emission, reference, and transmission holders equipped with optimized optical components to achieve the purposes.

ZEMAX optical simulations were systematically performed to evaluate the performance of various lens configurations and their focusing behaviour, leading to an optimized optical setup.

The significance of this project lies in demonstrating that a compact, dual-mode optical platform can potentially deliver rapid, non-destructive, and multi-parameter water quality measurements. By leveraging the simultaneous usage of FLU and UVA/T detection, the system provides complementary data about the contaminants in the sample, enabling more reliable and accurate analysis.

Moving forward, future work can focus on further miniaturization of the prototype, integration of advanced microcontrollers for automated data handling, and refinement of the fluorescence detection optics. These improvements will help advance the system toward a deployable, field-ready solution supporting Singapore's long-term water sustainability and environmental monitoring goals.

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Another special thanks go to the EE3180 Design and Innovation Project (DIP) group members, who worked collaboratively with the team and contributed extensively to the 3D modelling and printing of the prototype's mechanical structure.

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