Paper 08 / 2021 doi: 10.7795/320.202108

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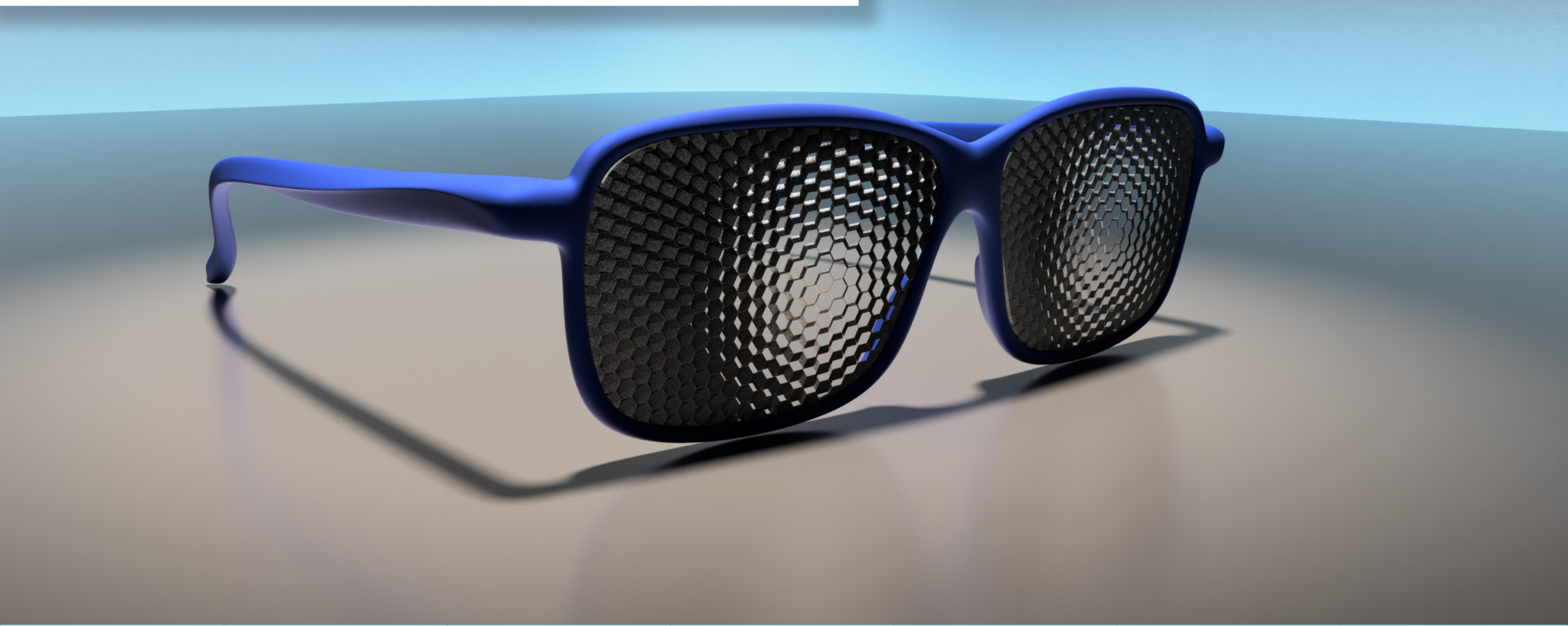
JungforscherInnen publizieren
online | *peer reviewed* | original

Verlag:
Physikalisch-
Technische
Bundesanstalt
PTB



Technik

# Optimization of a Self-darkening System

## Effect of a resistor in series with an optically addressed spatial light modulator on the input and output light intensity curve

*As the characterization of self-darkening systems (OASLM: Optically Addressed Spatial Light Modulator) for smart sunglasses is very cost and time intensive, the aim was to explore the ability to optimize OASLM systems using series resistances. It was found that series resistances between 0 MΩ and 40 MΩ can manipulate a given darkening curve to fit pre-set conditions for the use in smart sunglasses.*

DER JUNGFORSCHER

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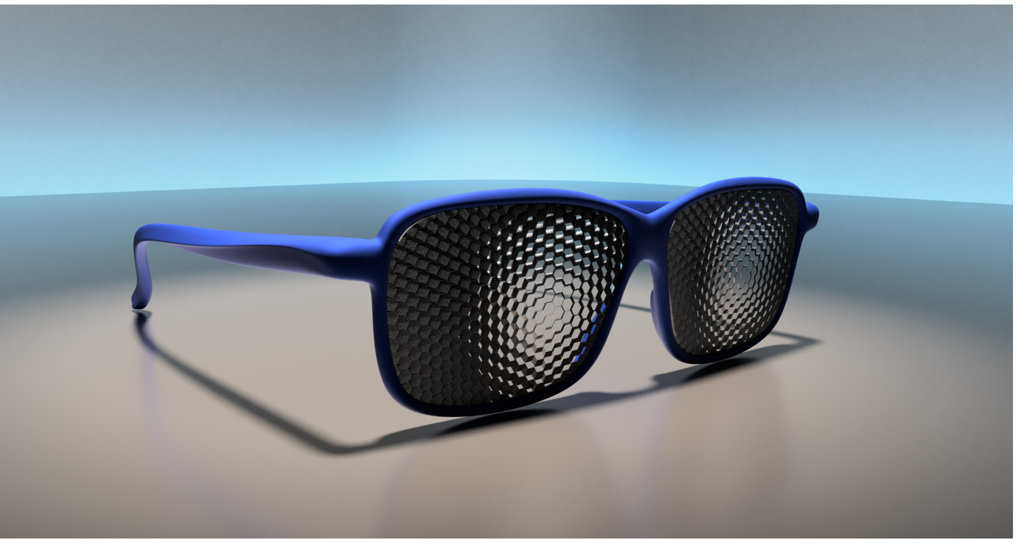
**Eingang der Arbeit:**
6.2.2020
**Arbeit angenommen:**
27.5.2020



# Optimization of a Self-darkening System

## Effect of a resistor in series with an optically addressed spatial light modulator on the input and output light intensity curve

## 1. Introduction

It is always unpleasant and dangerous to be blinded by glaring light, whether from the setting sun or bright arc welding flashes. Unfortunately, conventional darkening methods such as sunglasses or welding goggles provide a small improvement in visual perception in intense light conditions. Due to this, autonomous optically addressed spatial light modulators (OASLM) have moved into the interest of the industry. These provide the benefit of reacting autonomously to the current light intensity and actively manipulate the light intensity that falls onto them.

However, due to the broad application possibilities, it is necessary to fine-tune or optimize these components to meet the requirements of the intended application. Thus, in the following essay, the possibility of using series resistors for the optimization of an OASLM system for sunglasses will be explored.

### 1.1 Research Question

The idea behind this optimization method is to introduce an external resistor in series with the darkening system, which will be used to fine-tune the system. This proposed optimization process can cost-efficiently provide the resistive parameters required for different OASLM systems. In order to assess the viability of this optimization method, the following experiments will attempt to answer the research question: What is the effect of a series resistor on the input/output light intensity curve of an optically addressed spatial light modulator?

### 1.2 Theory

To understand the working principle behind this optimization technique, it is essential to understand how an OASLM works and the interplay of the different components.

#### 1.2.1 Principles of Optically Addressed Spatial Light Modulators

Optically addressed spatial light modulators (OASLM) can detect and modulate incident light accordingly using a photodetector and a light modulator, respectively [1]. Fig. 1 shows a diagram of the potential layout for an OASLM. There are many different variations of OASLM systems such as phototropic liquid crystal systems [2], liquid crystal systems with a surface-induced orientation via phototropic alignment layers of organic films [3], and organic solar cell and liquid crystal cell based systems [4].

#### 1.2.2 Organic Photovoltaic Cells

A semi-transparent heterojunction organic solar cell can be used as a photodetector as it produces a signal when it detects incoming light and allows for a portion of the light to pass through.

Heterojunction organic solar cells consist of a blend of polymers (donor) and fullerenes (acceptor) and use the photovoltaic effect to generate a potential difference across its electrodes. If photons of frequency $f_{photon}$ are incident on the conjugated polymers in the photoactive material, where $f_{photon} > f_{threshold}$, then an exciton (see glossary) is generated. This exciton then separates into an electron/hole pair due to the polarity difference between the donor-acceptor-heterojunction (see glossary). This electron/hole pair is then pulled apart due to an electric field

doi: 10.7795/320.202108

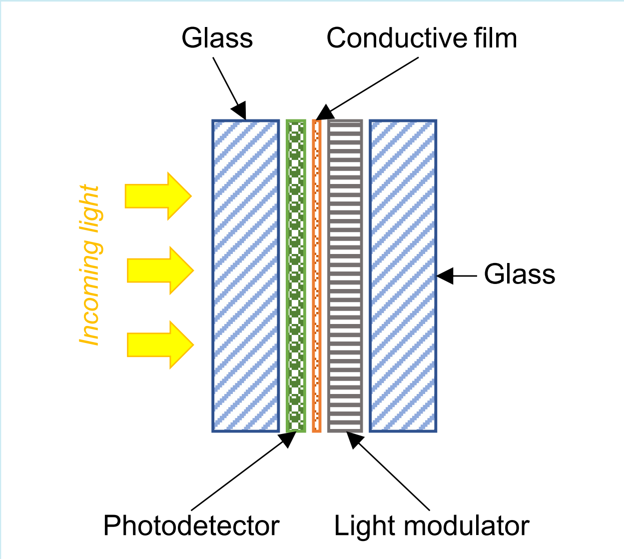


Fig. 1: A diagram of a potential layout for an optically addressed spatial light modulator (OASLM).

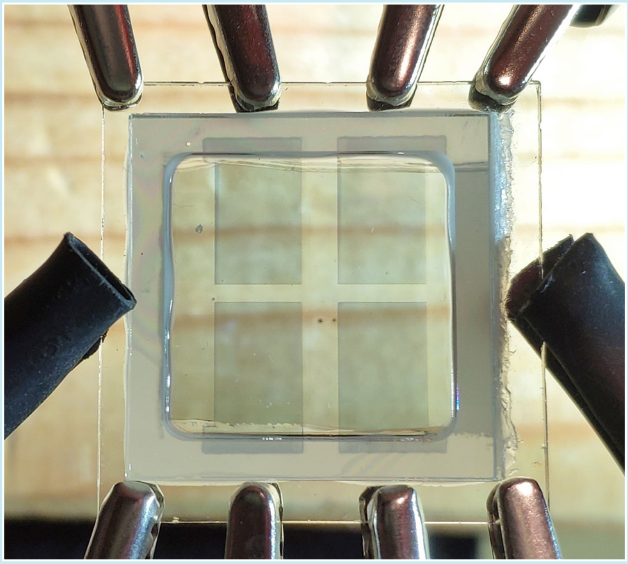


Fig. 2: An organic solar cell (OSC) with four individual cells connected in series with crocodile clips.

between two exterior materials, causing the cathode and anode to become charged [5].

Recent developments have revealed that organic solar cells (OSC) based on a non-fullerene can achieve a higher open-circuit voltage $V_{OC}$: (see glossary) [6]. Thus, in this exploration, an OSC with the non-fullerene indacenodithiophene-based small molecule O-IDTBR will be used (Fig. 2).

### 1.2.3 Liquid Crystal Cells

A liquid crystal (LC) system can be used as an effective light modulator as it reacts very quickly to changes in the input signal and it can modulate the light waves through a large range ($\frac{\pi}{2}$ *rad*).

Liquid crystal systems are electrochromic light modulators (see glossary) that can manipulate the transmitted light intensity. In their natural state, the twisted orientation of the molecules rotates the plane of incident polarized light by 90°, allowing the light to pass the analyser. Once an electric signal of the voltage $V_{input}$ is applied, where $V_{input} > V_{threshold}$ (see glossary), then the polar LC molecules orientate themselves along the electric field lines. As the light plane is not rotated, the incident light is now absorbed by the analyser [7]. Figure 3 depicts the clear and dark state of an LC cell.

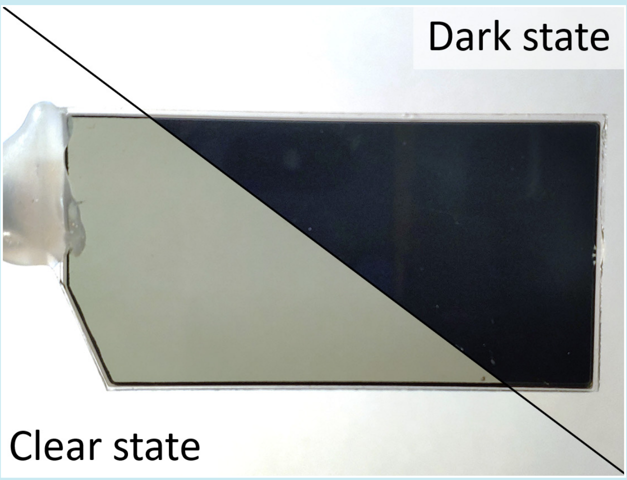


Fig. 3: View through the liquid crystal cell during the clear and dark state.

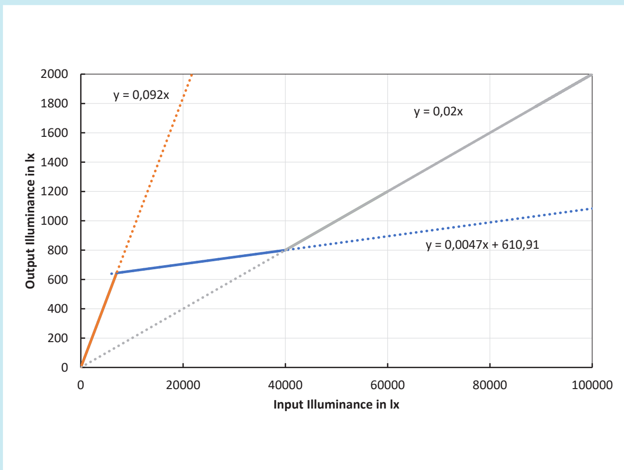


Fig. 4: Optimal output/input illuminance curve.

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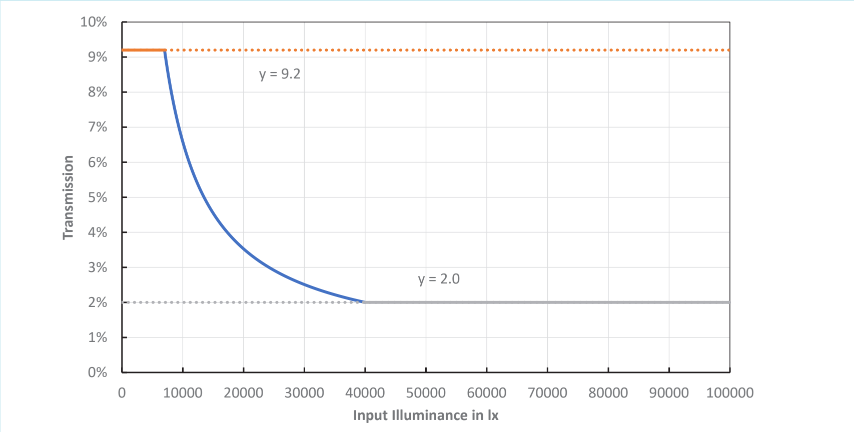


Fig. 5: The optimal transmission characteristics curve ranging between 9.2 % and 2.0 % transmission.

It is well known that the transmission range (see glossary) of LC cells decreases over time if powered with a DC power source due to ion movement. However, as the rate of transmission range loss per minute (clearing of LC cell with respect to time) was found to be $6.5 \times 10^{-6}$ %· $\text{min}^{-1}$, this limitation was determined to be negligible and thus it was assumed that the LC cells could be powered by the DC current from the OSC.

## 2. Deriving the Optimal Characteristic Curve

The optimal input/output illuminance curve and transmission curve that should be reached by the OASLM system can be seen in Figure 4 and Figure 5 respectively. The optimal system is defined according to the given transmission range demonstrated by the OASLM system. The transmission range is between 9.2 % and 2.0 % and is dictated by the physical properties of the LC and OSC. It is further defined, that the system is most transparent in low light intensities (illuminance < 10000 lx) and the output illuminance does not exceed 3000 lx at 100000 lx. It must be noted that this optimal curve is strongly dependent on the personal perception of light intensity and therefore contains a certain degree of arbitrariness. An improved optimal function is derived in the chapter 6.3.

## 3. Development of the Components

### 3.1 Transmission Meter Apparatus

Due to the inaccessibility of a transmission meter, a custom-built system was constructed, which also ensured high repeatability (see Figure 6).

The transmission meter uses two lux light meters (BH1750 by Rohm Semiconductor) that are connected to a single board computer (Raspberry Pi). These sensors output a signal that expresses the illuminance they are subjected to.

Additionally, a dimmable 30 W LED spotlight was required. The driving voltage for this LED was supplied

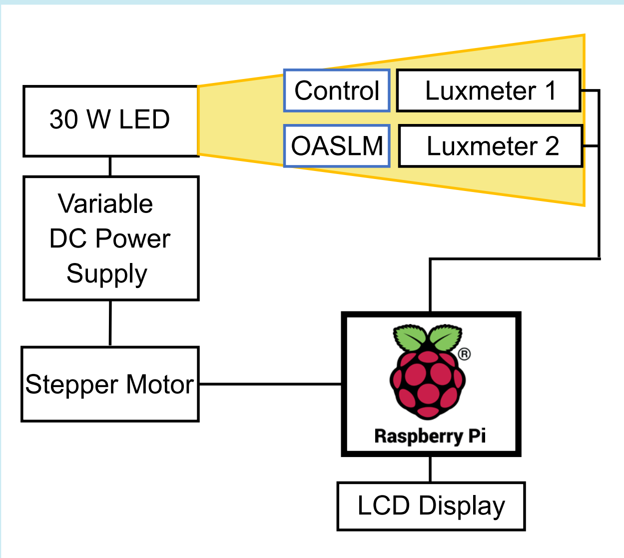


Fig. 6: A schematic diagram of how the major components of the transmission meter were connected and positioned.

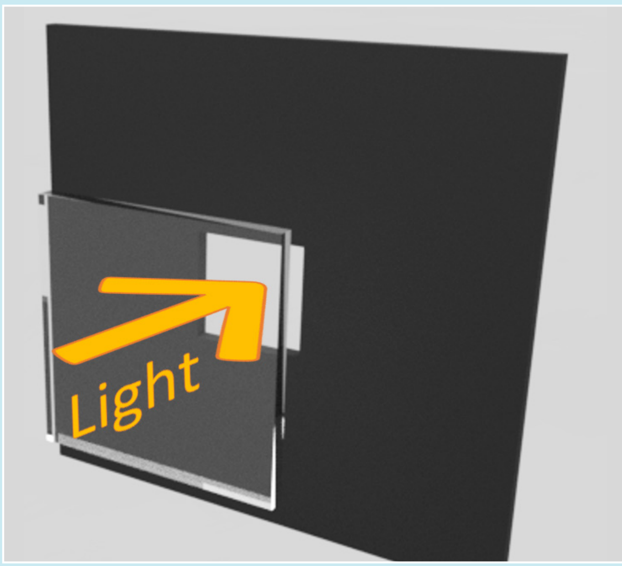


Fig. 7: CAD render of an aperture and a glass cover used to simulate the light blockage by the components of the OASLM.

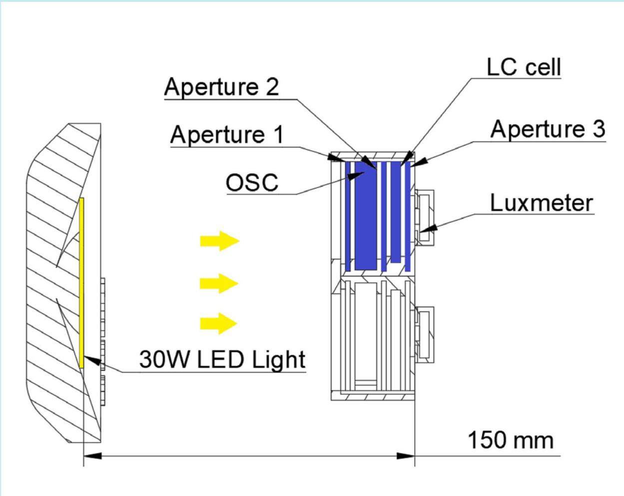


Fig. 8: Construction drawing of the transmission meter setup and the setup of the transmission meter casing.

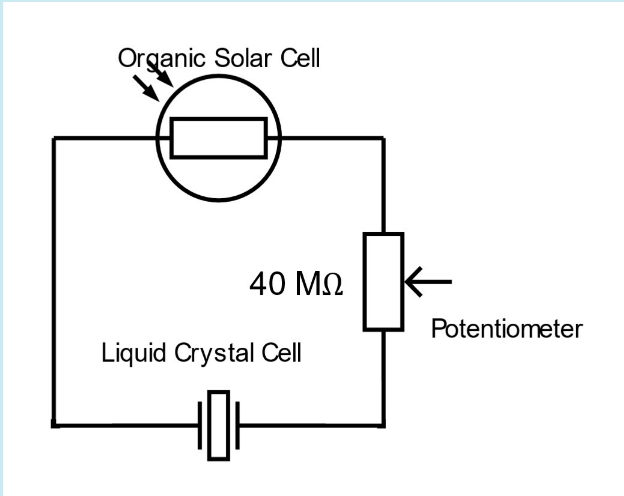


Fig. 9: The circuit diagram for the OASLM system

by an external DC power supply (Maisheng MS 305D), which was controlled by a stepping motor. In a single light intensity measurement sweep, the motor would automatically and reliably increase and decrease the input voltage between 0 V and 30 V. Each light intensity measurement sweep takes about 145 seconds and the maximum illuminance reached is 40 000 lx ± 8000 lx (measurement accuracy from the BH1750 lux meters taken from the datasheet [8]). The rate of change of light intensity is about 1020 lx ± 10 lx/s (1000 lx light intensity increase is equivalent to a well-lit room). The LED spotlight was placed about 150 mm equidistant from both luxmeters (see Figure 8). Whilst one of the luxmeters measured the light intensity through the OASLM system, the other measured the incident light intensity without the OASLM. The fraction of these values expresses the overall transmission of the OASLM system.

$$Transmission = \frac{I_{with\ OASLM}}{I_{without\ OASLM}} \cdot 100\ \%$$

The python code used to run this system was written by the author. Figure 6 shows how the major components of the transmission meter were connected. Figure 9 shows a simplified circuitry plan of transmission meter.

The OSC and LC cell were fixated in a holding mount that was designed using a CAD program (Autodesk Fusion 360) and then 3D printed via an FDM and DLP 3D printer (see Figure 7).

This mount ensured that the components were positioned directly infront of one of the luxmeters. Finally, to compensate for the light absorbed or reflected from the LC and OSC glass bodies, equally sized apertures and glass plates were placed in front of the luxmeter without the OASLM to simulate the amount of light blockage and reflectance due to the components of the OASLM (see Figure 7 and Figure 8).

Tab. 1: Characteristic data of the OSC and the LC cell.

| | Transmission in % | Voltage in V | Current in µA |
|---|---|---|---|
| OSC | 22.1 | $V_{oc}$: 2.73 ± 0.01 at 39 200 ± 100 lx | $I_{sc}$: 60.93 ± 0.01 at 39 200 ± 100 lx |
| LC Cell | 39.0 | $V_{Th}$: 1.22 | I: 0.04 ± 0.01 at 2.73 ± 0.01 V |
| Stacked | 9.2 | | |

### 3.2 OASLM System

The following autonomous OASLM system has been developed independently by the author and is used in the following exploration. The OASLM system comprises of a semi-transparent organic solar cell stacked in front of a twisted nematic (TN) liquid crystal cell (Figure 8 for a construction drawing of this layout and see Table 1 for further data regarding the OSC and LC cell).

This OASLM was then optimized with respect to its optical throughput using a 40 MΩ potentiometer put in series with the liquid crystal cell. This potentiometer was used to simulate distinct resistances with increments of 5 M values (Figure 9). The maximum

Tab. 2: The resistance values in series with the LC cell simulated by the potentiometer.

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Series Resistor in MΩ (±1 MΩ) | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 |

transmission of the OASLM system was found to be 9.2 ± 0.1 %.

Figure 10 and Figure 11 show the input/output illuminance and the pure transmission curves, respectively.

As can be seen especially in Figure 10, the resultant light intensity that reaches the eye does not follow the optimal curve from Figure 4. More specifically, the transmission curve of the LC and the voltage output curve of the OSC are not harmonised, leading to an input/output peak between 10 000 lx and 15 000 lx and a dip at 30 000 lx. In fact, even as the input illuminance increases between 12 000 lx to 30 000 lx, the perceived light intensity by the eye has a negative slope. This manipulates the light perception by the wearer and is not ideal. Using Figure 11 it can inferred that the rate of change of transmission with respect to input illuminance is too steep and must be flattened. Thus, it was explored to what extent a series resistor could be added into the circuit to optimize the characteristics curve. Finally it can also be inferred, that Figure 10 would show a positive slope after 30 000 lx as the function asymptotically approaches a gentler slope than between 0 – 10 000 lx due to the smaller transmission value.

## 4. Hypothesis

It can be expected that reducing the effective voltage from the OSC by adding a resistor in series with the liquid crystal cell could have the effect of stretching the input/output illuminance characteristic curve along the y-axis. This stretch is caused by a decrease in potential difference falling across the LC cell. Further, the OASLM might have a decreased transmission range as the new $V_{OC}$ that reaches the LC will be lower.

Additionally, it can be expected that the addition of a series resistor might result in a stronger time dependent retardation effect. As liquid crystals behave like a capacitor, a series resistor might make it more difficult for the charge to dissipate and consequently the OASLM system might show a slightly longer delay when clearing up.

## 5. Transmission Curve Recording Process

For each trial, the python script was executed, after which the programmed testing light intensity measurement sweep was completed. The readings measured by the sensors were programmed to be written into a table. The entire process was repeated for all the resistance configurations, as can be seen in Table 2 (for control curves see Figure 11 and Figure 10). Figure 12 shows the characteristic curves with different series resistances.

## 6. Data processing

In order to determine the degree of optimization, the input/output

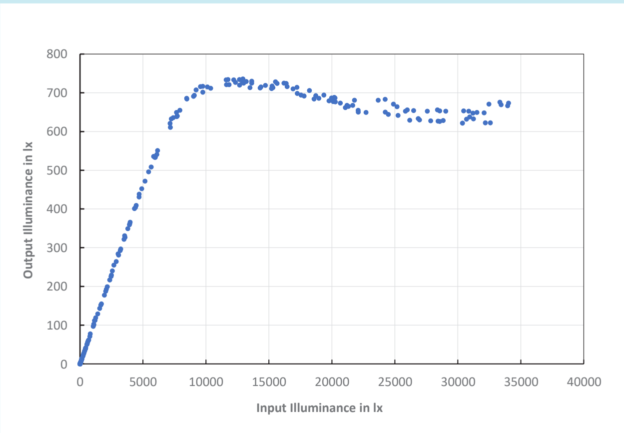


Fig. 10: The OASLM output illuminance behind the stacked cells as a function of input illuminance with a series resistance of 0 MΩ.

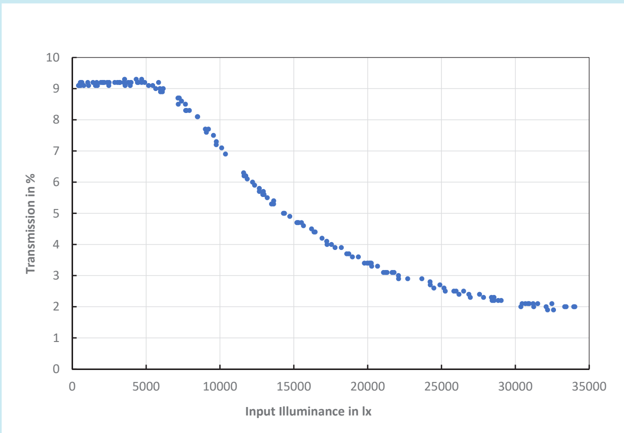


Fig. 11: The OASLM transmission characteristics curve with a series resistance of 0 MΩ. The transmission can be seen to approach 9.22 % transmission below 5000 lx and 2.00 % transmission above 32 000 lx.

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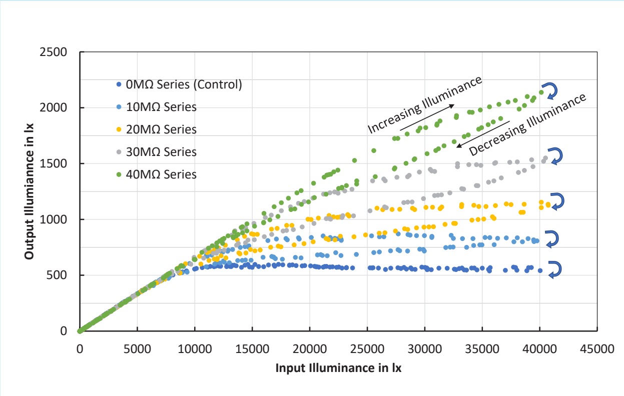


Fig. 12: The effect series resistors from 0 – 40 MΩ have on the input/output illuminance curve of an OASLM

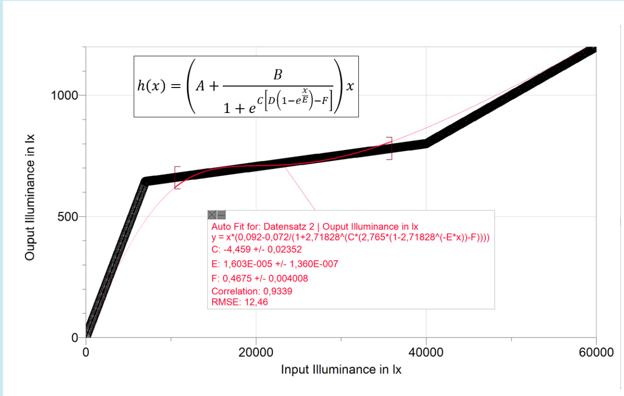


Fig. 13: A graphical representation of the derived OASLM approximation function.

illuminance characteristic curves were then evaluated according to transmission loss, the retardation, and the coefficient of determination ($R^2$ value). The respective optimization indicator values for each characteristic curve were recorded in Table 4.

## 6.1 Transmission Loss

Transmission loss is the percentage of transmission range loss with respect to the transmission range of the control OASLM characteristics curve. The function used to determine transmission loss is Formel 1.

## 6.2 Retardation

A retardation can be observed when the characteristic curve recorded during increasing light intensity differs to the characteristic curve during decreasing light intensity. This effect is caused by the slow clearing of the LC cell. The light intensity measurement sweep has an increasing and decreasing rate of illuminance per unit of time of 1020 lx ± 10 lx/s. The degree of the retardation is calculated with the following formula 2. It determines the average difference between all single upwards transmission values and their respective downwards transmission values given as a percentage of the given transmission range.

The fifty values before and after maximum illuminance were used to decrease systematic error exhibited by the asymmetric behaviour of the light intensity measurement sweep.

$$Transmission\ loss = \left(1 - \frac{\Delta\, Trans_{system}}{\Delta\, Trans_{0M\Omega}}\right) \times 100\,\% = \left(1 - \frac{Trans_{max\ of\ system} - Trans_{min\ of\ system}}{Trans_{max\ of\ 0M\Omega} - Trans_{min\ of\ 0M\Omega}}\right) \times 100\ \%$$

Formula 1

$$Retardation = \left(\frac{\overline{Trans}_{down} - \overline{Trans}_{up}}{Trans\ Range}\right) \times 100\,\% = \left(\frac{\left(\sum Trans_{172>t>122}/n\right) - \left(\sum Trans_{71<t<121}/n\right)}{Trans_{max} - Trans_{min}}\right) \times 100\ \%$$

$$Trans_{172>t>122\ sec} = Transmission\ values\ from\ trial\ 122 - 172\ sec^{*)}$$

$$Trans_{50<t<122\ sec} = Transmission\ values\ from\ 71 - 121\ sec^{*)}\ n = Total\ number\ of\ values\ in\ trial\ range$$

*) The fifty values before and after maximum illuminance were used to decrease systematic error exhibited by the asymmetric behaviour of the light intensity measurement sweep.

Formula 2

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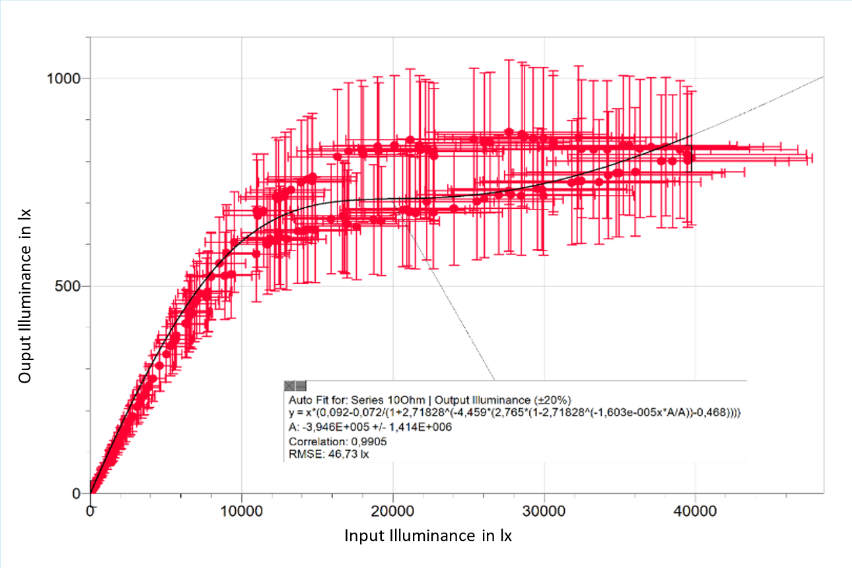


Fig. 14: The characteristic curve of the OASLM with a 10 MΩ resistor in series. The optimal function is shown with a solid line.

## 6.3 Coefficient of Determination $R^2$

The coefficient of determination gives a great indicator of the degree to which the optimal curve is reached in each trial. The piece-wise function derived in chapter 2 was used as a foundation to develop a more realistic optimal function. This improved function is a composite of the individual characteristic curves exhibited by the LC and OSC. A graphical representation, and the function can be seen in Figure 13.

This complex formula can now be used to model many different OASLM materials as it is composed of the characteristics curve of the individual components. This complex formula is then fitted to the optimal linear function derived at the beginning. The interpretation of each variable in the function and its respective optimal value can be seen in Table 3.

Tab. 3: The graphical interpretation and optimal value of the variables in the approximation function.

| Variable | Interpretation | Optimal Value |
|---|---|---|
| A | Maximum transmission | 0.092 |
| B | Transmission range | −0.072 |
| C | Gradient at point of inflection | −4.459 |
| D | Open-circuit voltage | 2.765 |
| E | Gradient at origin | $1.603\times10^{-5}$ |
| F | Domain of point of inflection | 0.468 |

The $R^2$ correlation between the recorded characteristic curves and the optimal function was determined using Logger pro 3.10.1. See Figure 14 for an analysis example of the $R^2$ value between the 10 MΩ series resistor characteristic curve and the optimal function.

## 6.4 Uncertainty Calculation and Error Propagation

The accuracy value for the BH1750 luxmeters was taken directly from the datasheet [8]. The light meters have an accuracy value of 20 % and can measure up to 0.5 lx.

# 7. Results

The coefficient of determination, the percentage of transmission reduction, and the percentage of retardation values were graphed against their respective resistance values and are shown in Figure 15, Figure 16, and Figure 17.

## 7.1 Coefficient of Determination Analysis

The coefficient of determination $R^2$ can be seen to increase from about 0.91 to about 0.99 between 0 MΩ and 10 MΩ. Following it decreases, to about 0.87 at 40 MΩ. A simple cubic trendline function provided the strongest correlation with the data up to 40 MΩ. Above 40 MΩ the results should theoretically decrease further before saturating and reaching a constant coefficient of determination. However, if the domain of the characteristic curve were to be extended to values greater than 40 MΩ, respective dampening terms should prevail that hinder the cubic function from increasing again. Further, as the variables of this cubic function do not represent any physical observations of the OASLM system, these values cannot be examined any further. However, an extension could be to develop a more accurate approximation curve of the data, possibly using a composite function

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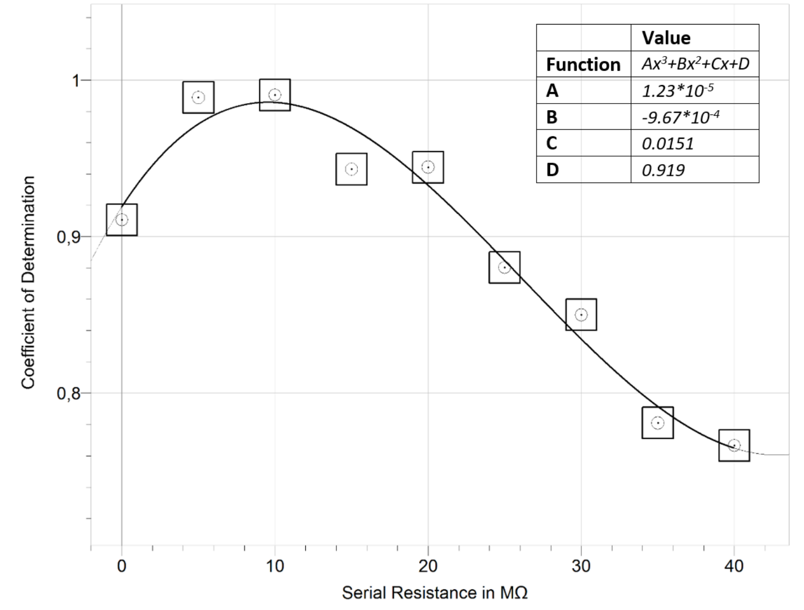



Fig. 15: The coefficient of determination due to an increasing series resistance.

of the logistic growth function of the current characteristics curve of the LC and the exponential decay (decreasing form) function of the OSC.

The local maximum with the highest coefficient of determination can be found using the derivative of this cubic function and solving for zero (see below). This allows us to determine that a series resistance of 9.5 MΩ provides the highest coefficient of determination with 0.99 and therefore a series resistance of this magnitude would allow us to reach the most optimized OASLM system given the previously defined light intensity conditions.

The coefficient of determination values at 5 MΩ and 15 MΩ are slightly offset. This is probably due to the random error exhibited by contacts within the OSC structure itself.

## 7.2 Transmission Reduction Analysis

The series resistance and resultant transmission reduction can be seen to have a proportional relationship (see Figure 16).

The function mapping these two variables should hypothetically fall through the origin because a series resistance of 0 MΩ would not affect the OASLM in any way. Therefore, it can be proposed that the series resistance $R_S$ is proportional to the ratio of transmission reduction. A transmission reduction of 70 % is reached at 40 MΩ series resistance. This linear relationship can be mapped by the following function:

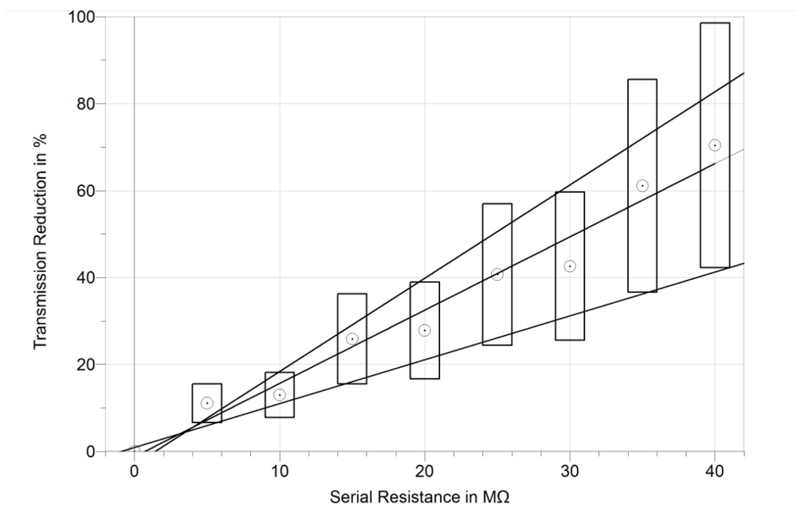
$$f(x) = 1.69x - 1.2$$

The slope of 1.69 %/MΩ indicates that there will be an increase in the percentage of transmission reduction of 1.69 % per MΩ of series resistance that is added in series with the OASLM system.

Using the uncertainty expression $\frac{Slope_{Max} - Slope_{Min}}{2}$ an absolute uncertainty of ±1.14 %/MΩ can be determined. Further the y intercept of −1.20 % indicates a systematic error. However, this error is not very significant as it is very small in comparison to the recorded values up to 70 %.

## 7.3 Retardation Analysis

The results show that there is a proportional relationship between the




| | Slope (%/MΩ) | Y-Intercept (%) |
|---|---|---|
| Average Linear Fit | 1.69 | -1.20 |
| Maximum Linear Fit | 2.15 | -3.06 |
| Minimum Linear Fit | 1.01 | 0.92 |

Fig. 16: The percentage of transmission reduction due to an increased series resistance

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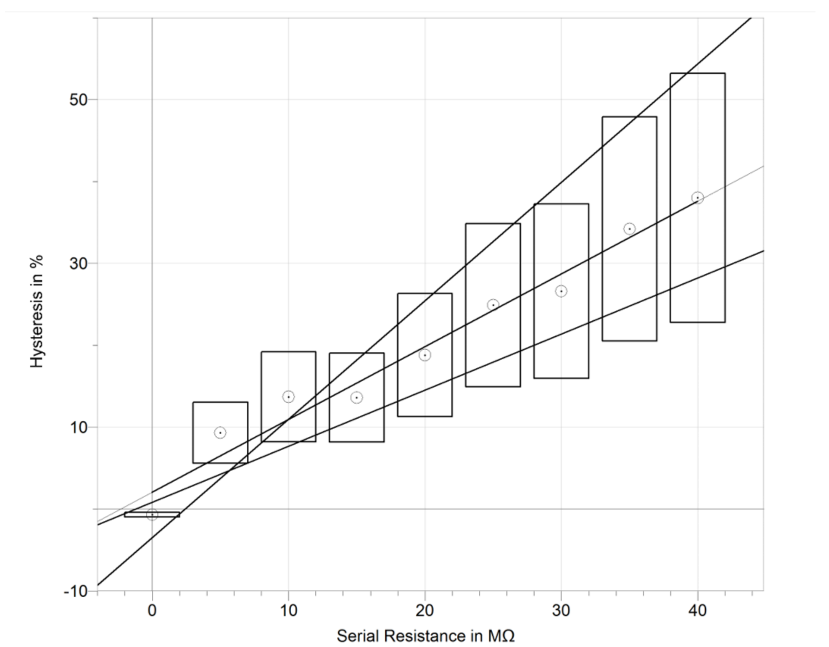


| | Slope (%/MΩ) | Y-Intercept (%) |
|---|---|---|
| **Average Linear Fit** | *0.89* | *2.05* |
| **Maximum Linear Fit** | *1.45* | *-3.52* |
| **Minimum Linear Fit** | *0.68* | *0.81* |

Fig. 17: The percentage of retardation due to an increasing series resistance.

series resistance and the retardation (see Figure 17).

The maximum observed retardation is 38 % at a series resistance of 40 MΩ. This data distribution can be represented by the following linear fit function:

$$f(x) = 0.89x + 2.05$$

The slope of 0.89 shows that there is 0.89 % retardation increase per 1 MΩ of resistance added in series with the OASLM system. The absolute uncertainty was found to be ±1.07 %/MΩ. Further it is suspected that the system would pass through the origin. This, however, is not the case as the trendline shows a y intercept of 2.05 %. This is probably due to a systematic error in the testing rig. Additionally, the control value at 0 MΩ series resistance shows that a negative retardation value of –1 % was obtained. However, due to the lack of a possible explanation, it is assumed that this is due to a random error in the setup (i. e. shifting of the transmission meter or OASLM).

## 8. Analysis

When a series resistor is added to the LC cell, then a smaller portion of the electromotive force (emf) will fall off the LC cell. This means that a series resistor of increasing resistance would compress the $V_{OC}$ characteristics curve of the OSC along the output-illuminance-axis. This has the effect of decreasing the $V_{OC}$ (variable “D” in Table 3) and the rate of change in emf per unit of light intensity. If the series resistance is too low, then the OASLM will reach minimum transmission to early and if the series resistance is too high, then the OASLM system will not darken enough. The series resistance of 9.5 MΩ provided the most ideal curve (see Figure 15).

As the LC draws a current of 0.04 μA at 2.73 V, Ohm’s law can be used to determine that 0.38 V of the $V_{OC}$ was lost through the resistor. This means the effective potential that was supplied to the OASLM was 2.75 V.

Figure 16 further shows, that at the given series resistance, there will be a transmission range reduction of 14.9 %. The effective transmission range will therefore be decreased from 7.2 % to 6.1 %. This shows that not enough potential difference reached the LC cell. This allows us to conclude that the LC cell required all of this emf to turn dark, however, after flattening the OSCs gradient using the resistor, some of this effective voltage was lost. From this we can infer that this method of optimization is best if the OSC provides more than enough $V_{OC}$ for the LC to reach minimum darkness. The series resistor can then be used to decrease the rate of change in emf per unit of light intensity without affecting the transmission range.

The addition of a resistor in series, however, has the downside of making it more difficult for the built-up charge in the LC cell to discharge. Therefore, a retardation is seen in the second half of the light intensity measurement sweep when the charge must dissipate through the circuit. Figure 17 shows that a series resistance of 9.5 MΩ would lead to a retardation of 10.5 %. If applied to the transmission range of 6.1 %, it can be calculated that there will be a 0.6 % smaller average transmission value during the decreasing light illuminance process.

In conclusion, the results indicate, that the hypothesis is true. A series resistor can be used to optimize a given OASLM characteristic curve. It was found that a series resistor of 9.5 MΩ increased the coefficient of determination of a given characteristic curve from 0.92 to 0.99. This, however, had the effect of increasing the retardation by 10.5 %. This retardation might have been

Tab. 4 : The effect of a series resistor on the transmission range, transmission loss, retardation, and coefficient of determination of the OASLM system

| Series Resistance in MΩ (±1 MΩ) | Transmission Range in % (±20%) | Transmission Reduction in % (relative to control) (±40%) | Retardation in % (±40%) | $R^2$ Coefficient of Determination (relative to optimal curve) (±0.01) |
|---|---|---|---|---|
| | $Trans_{max} - Trans_{min}$ | $\frac{Trans_{range}}{Trans_{0M\Omega}}$ | $\frac{\overline{Tr_{up}} - \overline{Tr_{down}}}{Trans_{range}}$ | $R^2$ |
| 0 | 5.4 | 0 | -1 | 0.91 |
| 5 | 4.8 | 11 | 9 | 0.99 |
| 10 | 4.7 | 13 | 14 | 0.99 |
| 15 | 4.0 | 26 | 14 | 0.94 |
| 20 | 3.9 | 28 | 19 | 0.94 |
| 25 | 3.2 | 41 | 25 | 0.88 |
| 30 | 3.1 | 43 | 27 | 0.85 |
| 35 | 2.1 | 61 | 34 | 0.78 |
| 40 | 1.6 | 70 | 38 | 0.77 |

the cause as to why a coefficient of determination of ~1.0 could not have been reached. Another reason might have been, that the series resistor had decreased the transmission range by 14.9 % and therefore, a minimum transmission of 2.0 % at maximum light intensity, as described in the optimal curve, could not be reached.

## 9. Evaluation

As the luxmeters have an uncertainty of 20 %, all consecutive values that are calculated with these values, will have a minimum percentage uncertainty of 20 %. This indicates that the results are not very precise and therefore, the conclusions drawn from the data are limited by the degree of uncertainty. This percentage uncertainty can be decreased by using other more precise luxmeters that are designed for lab style optical tests. The BH1750 luxmeters used in this experiment were developed for the use in phones and thus have not be designed to provide very precise measurements.

However, once any readings fall close to 0, as in Figure 15, then the absolute uncertainty values decrease significantly, and random errors start to show. Due to this, a trendline can only be applied to the data with great difficulty. The fluctuations in Figure 15 of ±2 % reveal random errors in the testing rig itself. Possible sources of random errors could include the lack of complete fixation of the transmission meter rig. The sensor mount for example was able to swivel, which could have caused an imbalance of light illuminance on both luxmeters. This can be improved by properly fixating the mount to the optical bench and redesigning the sensor mount. Additionally, these random errors can have also be caused by the light source itself. The power supply providing the driving voltage did not output a smooth power output, causing the light to flicker sometimes. As the input and output illuminance readings were taken at the same time, this should not have a large effect. However, as the OASLM system lags slightly, this might have caused the observed fluctuations in the data. This problem can be addressed by adding a smoothening capacitor into the LED spotlight circuit, so that the voltage spikes can be smoothened out.

Due to the limitations of the code, it was not possible to perform a zero-value calibration of the light sensors in situ. Therefore, the default calibration of the sensors was used. This has probably caused the y-intercept offset and systematic errors observed in Figure 16 and Figure 17. This can be improved by adapting the code to perform a calibration before each measurement.

## 10. Conclusion

The results support the hypothesis that a resistor in series with the LC cell of an OASLM system allows us to optimize the characteristics curve of such systems. It was found that a series resistor of 9.5 MΩ

doi: 10.7795/320.202108

can optimize a given input/output illuminance curve from a coefficient of determination of 0.91 to 0.99. This would, however, decrease the effective transmission range by 14.9 %. Further, this resistor causes the appearance of a retardation of magnitude 10.5 % at a rate of change of light intensity per second of 1020 lx/s ± 10 lx/s.

Thus, it was found out, that it is advantageous to add a resistor in series with the LC cell of the OASLM system in order to optimize the characteristics curve. Hereby the rate of change in emf generation per unit of light intensity can be manipulated. A parallel resistor could then potentially be used to fine tune the curve to decrease the effects of a retardation. As the retardation is strongly dependent on the rate of change of light intensity per second, this area still underlies further research into how the parallel resistor effects the reaction speed of the system. From the given results, it can further be concluded that only specific OASLM systems with a solar cell and electrochromic substance, such as a LC cell, can lend themselves to this type of optimization. Further OASLM systems with a OSC that generate a greater $V_{OC}$ at the light intensity of minimum transmission than the LC requires are favoured because this allows a series resistor to decrease the rate of change of emf generation per unit of light intensity without hindering the LC to reach minimum transmission at maximum input voltage.

The solar simulator was only able to reach an illuminance level of 40 000 lx and used the emission spectrum of a white LED. This meant, that the input/output illuminance characteristic curve was not able to support a conclusion regarding the effect of natural sunlight on the OASLM system. This problem can be solved by using a solar simulator in order to characterize the characteristic curve for a broader range of light intensities and light frequencies over the entire UV-VIS spectrum. However, it can be assumed that the OASLM system would reach minimum transmission and might even turn a little darker under natural sunlight due to the increased intensity.

Further, an improved optimal function can be derived by using a multi component blend model of the logistic growth function and exponential growth function to map the characteristics curve of the LC and OPV. This is because the LC cell and OSC cell both are comprised of a blend of different materials that all have different characteristics curves and thus a single function would only represent the average curve of all molecules present in the mixture. It must also be recognized that the conditions used to define the optimal curve are by a certain degree chosen arbitrarily, especially as the optimal curve is strongly dependent on the wearer's perception of light intensity. This means that the approximated optimal curve might have to be adapted for different uses and applications.

However, the composite-function that was used to model the OASLM system within this experiment already is a great approximation of the OASLM system and thus the principles of this formula can be used to fit many different new substances for the OASLM components.

Finally, for the OASLM system to be implemented into smart sunglasses, it is necessary to increase the transmission range. This can be achieved by using more transparent OSC cells, as well as using higher grade polarisation filters that will truly block only half of the incident light. Additionally, adding a series resistor in circuit with the OASLM system (e.g. an external resistor or a specifically chosen conductive polymer or contacting material) will most of the times have the effect of decreasing the transmission range. This means, that this method of optimization should only be used to fine tune the OASLM system and coarse tuning should be performed by characterising and adapting the actual composition of the materials.

It would be interesting to investigate the effect other types of electrical components have on the characteristic curve. For example, phototransistors could ununiformly affect the rate of change emf generation per unit of light intensity and introduce a completely new light dependent variable. Also, if the OSC cannot provide enough $V_{OC}$, then it might be a great alternative to use the organic solar cell in combination with a battery cell and a transistor.

It can however be said that the exploration of OASLM has only started and bears great potential. It is without question that new technologies will arrive that will substitute the photodetector and LC modulation system. However, if the components rely on electrochemical substances, the ideas and concepts explored in this essay can still be applied to these new technologies.

## Glossary

**Exciton:** The bound state of an electron and an electron hole.

**Heterojunction:** The transitional area between two different semi-conductive materials.

**Open circuit Voltage $V_{OC}$:** the electromotive force generated when no load is applied to the circuit.

**Electrochromic:** the ability to change colour or transmission when charged with electricity.

**Threshold voltage $V_{TH}$:** the potential difference at which the liquid crystal molecules begin to rotate and the system becomes transmissive. It was defined to be the voltage at which transmission started to decrease by >1 %.

**Transmission range:** the maximum difference in transmission of a material's coloured/dark and clear state. This is found by $transmission_{max}$ – $transmission_{min}$.

**Transmission reduction:** the percentage of transmission range with series resistance > 0 MΩ in relation to transmission range of control curve with 0 MΩ series resistor.

**Retardation:** the percentage of average transmission value of increasing light intensity subtracted the average transmission value of decreasing light intensity with regard to total transmission range.

## Acknowledgements

The Light Technical Institute at the Karlsruhe Institute of Technology provided the organic solar cells required for these experiments. The Merck KGaA provided the liquid crystal cells required for these experiments. The free student version of the CAD program Autodesk Fusion 360 was used for the modelling, design, renderings, and construction drawings required for this research.

I would like to thank Priv. Doz. Prof. Dr.-Ing. Alexander Colsmann and his team at the LTI KIT to have supported this projected with the generous donation of the organic solar cells. Further I would like to thank the liquid crystal department of Merck KGaA for providing the liquid crystal cells. Finally, I would also like to thank Dr. Markus Jathe for his ongoing motivation and scientific guidance during the entire duration of this investigation.

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doi: 10.7795/320.202108

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doi: 10.7795/320.202108

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**Junge Wissenschaft**
c/o Physikalisch-Technische Bundesanstalt (PTB)
www.junge-wissenschaft.ptb.de

**Redaktion**
Dr. Sabine Walter, Chefredaktion
Junge Wissenschaft
Paul-Ducros-Str. 7
30952 Ronnenberg
E-Mail: sabine.walter@verlag-jungewissenschaft.de
Tel.: 05109 / 561 508

**Verlag**
Dr. Dr. Jens Simon,
Pressesprecher der PTB
Bundesallee 100
38116 Braunschweig
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Tel.: 0531 / 592 3006
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