Development of a finger vein acquisition device with side illumination

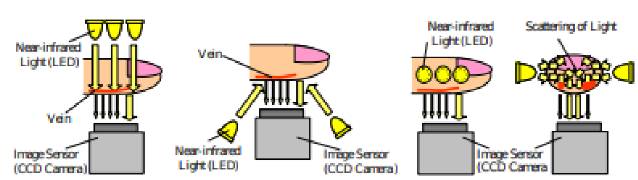
Serafym Kravchenko
Faculty of Electrical Engineering, Mathematics and Computer Science
University of Twente
Enschede, The Netherlands

***Abstract*—Biometrics centers around identification based on unique anatomical properties. Such unique properties, are finger vein patterns. These patterns can be recovered from vascular images. Vascular images are captured by near-infrared (NIR) light, which interacts with the finger causing vein projections on the skin. A common problem with these images, is that details in vein patterns reduce in the presence of overexposure. White areas, mostly found on the finger edge, are covering parts of the vein pattern. This effect occurs more often with side illumination. To mitigate this effect, suitable illumination must be applied. This research delves into the question if a side illumination setup can be designed with minimal presence of overexposure. By designing and individually evaluating multiple illuminators, the best suited illumination technique is to be chosen.**

***Index Terms*—Biometrics, Vascular image, Finger vein pattern, NIR, Illuminator, Overexposure, Radiation pattern**

I. Introduction

BIOMETRICS revolves around the concept of identification based on and grounded in distinctive biological attributes. An example of such a biological attribute is the layout of a person's finger veins (among more well-known examples such as fingerprints and iris scans). Research has consistently affirmed finger veins to be a unique identifier for an individual [1] [2]. Furthermore, it has been shown that this is a stable identifier over the course of a lifetime of an individual [1]. Given the non-intrusive nature of finger vein scanning, low error rates and impersonation resistance, vascular biometrics stands as a promising candidate in the realm of identification [1]. This kind of recognition is already commercially deployed and can be applied in the field of access control, authentication and security [3]. This is why finger vein recognition is an active research topic. Researchers have been continually active in exploring ways to harness the unique characteristics of vein patterns and enhance identification methods.



(a) Light transmission (b) Light reflection (c) Side lighting

Fig. 1: Transmission, reflection and side illumination acquisition [1]

The Data Management & Biometrics group (DMB) has been leading investigative efforts in the domain of vascular biometrics. Their work involves researching acquisition systems to extract vein patterns using varying techniques. One of the main elements in acquiring vein patterns is the illumination of the finger. For illumination, these systems utilize near infrared (NIR) light, since haemoglobin absorbs most of the light in that spectrum Figure 3. To light the finger, most systems illuminate the finger from above while capturing an image of the veins from below (using a NIR-sensitive camera). This illumination technique is called light transmission, which implies a closed-back design where the user has to put their finger inside an enclosed device. A drawback of this design is that it causes discomfort for the human scanning their finger [4] [1]. To avoid this problem, one can create a device in which the finger is illuminated from the side (allowing for an open-back design). This solves the discomfort of closed-back systems by allowing the user to place their finger on the device's surface without the need to insert it. Thereby maintaining visibility and ease of use throughout the system's operation. The use of side illumination is thus preferred over light transmission in terms of user-interface. However, such a design should still be able to capture qualitative vein scans.

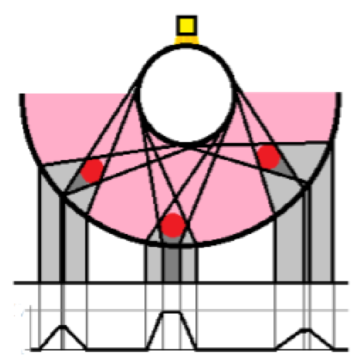


Fig. 2: Schematic model of the projection principle. Yellow square on top of the bone represents a light source. Finger tissue is presented by the pink area, and the red circles are the vessels [2]

NIR light can interact with the skin in several ways: it can be partially absorbed, transmitted into the skin's layers, or some of it can be reflected [1]. The desired effect is for the light to be uniformly distributed to all the veins. This can be achieved by focusing the light on the finger bone, which in turn diffuse the light through the entire finger. The veins will then absorb most of the diffused light, resulting in the projection of a shadow on the surface of the skin [2]. This phenomenon is illustrated in Figure 2.

A. Challenges of side illumination

When compared to light transmission, side illumination raises a few challenges. For one, it can create issues related to camera saturation due to broad NIR light beams [5]. In that case, it can result in saturation on the finger edges due to the reflection effect. As a light source diverges, outgoing rays may hit the camera without going through the finger tissue. This can either happen by the light rays directly hitting the camera or by reflecting off the skin into the camera. As a final result, the sides of the finger have a higher chance of being overexposed and thus the vein projections cannot be viewed for these areas. Moreover, the dynamic range of the image decreases in the presence of overexposure. Impeding results in general.

The primary research question driving this papers is: is *it possible to create a side illumination setup, while minimizing overexposure?*
The main objective of this research is to provide a side illumination design. Ensuring an open-back design and minimizing overexposure for improved vein pattern extraction and recognition. This objective can be divided in sub-questions:

1) *How can the improved side illumination be applied to capture vein patterns in high detail?*
2) *Which lighting design can minimize overexposure during side illumination?*

The first sub-question aims to achieve an illumination setup, with a more general view of the application. The latter sub-question relates to illuminator designs, that can mitigate overexposure. The answers to these questions will serve as a step to improve side illumination.

B. Paper structure

In section II, related work shall be discussed. This section contains information on relevant topics that can help answering the research questions. section III will show how this research can be approached by describing experiments and setups. The results of these experiments will be presented in section IV, while the interpretation of these results are evaluated in section V. Finally, a conclusion is given in section VI, where the research questions are answered.

II. Related work

This section focuses on context from existing knowledge. Former studies guide this research in answering the relevant research questions mentioned in section I. In order to answer these research questions, optics and the impact of light on image quality need to be examined. These optics help to understand how biological tissue interacts with incoming NIR light and form the principle of vascular imaging. the sub-question related to implementation of side illumination, can partially be answered by looking into how illumination is applied in previous designs. The effect of illumination on image quality answers sub-question related to minimizing overexposure. By understanding how illumination can be applied, a solution to both research questions can be proposed.

A. anatomical properties and optics

When NIR light (780 nm - 2500 nm) illuminates the finger, photons undergo interactions, including absorption and scattering [2]. Areas where photons are predominantly absorbed, appear dark to the camera. Notably, bone serves as a source of diffused NIR light throughout the finger[ref pesi]. Subsequently, when NIR light interacts with veins, most of it is absorbed by hemoglobin in the blood, resulting in the projection of the vessel on the skin's surface [2]. Moreover, as NIR light is diffused by the bone, it effectively serves as a secondary light source that interacts with the veins [ref pesi]. The consistency of the bone determines the extent of light diffusion. This projection principle is illustrated in Figure 2. In consumer products and experimental setups, NIR LEDs are commonly utilized for illumination [1] [3]. These LED's emit specific wavelengths within the NIR spectrum. Choosing a wavelength where hemoglobin absorbs more than water is essential to enhance the contrast between blood vessels and surrounding tissue.

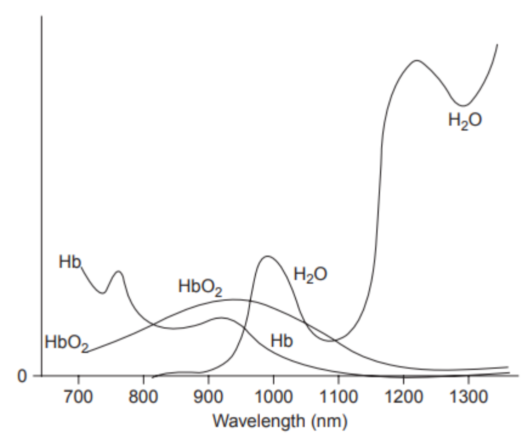


Fig. 3: Absorption chart for multiple substances. Horizontal axis: wavelength. Vertical axis: degree of absorption [1]

Figure 3 illustrates the absorption characteristics of water, oxygenated, and deoxygenated hemoglobin across varying wavelengths [1]. To effectively visualize blood vessels, it is essential for both oxygenated and deoxygenated hemoglobin to exhibit greater light absorption than water. As depicted in Figure 3, this condition is met at approximately 800 nm. Since the absorption rates of both haemoglobin variants are relatively similar at this wavelength, distinguishing between veins and arteries becomes challenging. Due to the diffusive properties of bone, the projection of vessels can still occur when illuminating the finger from various angles [5].

Anatomical properties, such as the composition of skin layers, distribution of fat cells, and vein depth, are unique for each individual [1] and beyond control. However, it is important to understand these natural differences. That is why exposure and brightness control is essential to adjust for these variations.

B. *Application of lighting*

Studies have shown the possibility of three distinct illumination methods [4] [1]:

1) Light transmission
2) Light reflection.
3) Side-illumination.

These different approaches are depicted in Figure 1.

1) Light transmission

In the context of transmission imaging, the light source and the camera are strategically positioned on opposite sides of the hand. Transmission allows light to pass through the finger without capturing surface reflections by the camera. This method stands out for its ability to produce clear and high-contrast images of vascular patterns [1].

2) Light reflection

In the case of light reflection, both the LED sources and the sensor are situated on the same side of the finger [1]. This allows the device to be more compact. During operation, the user is still able to see their finger since this method offers an open-back design. However, this configuration yields limited tissue penetration, resulting in weak contrast between vessels and surrounding tissue [1]. Moreover, reflected light often results in overexposure.

3) Side-illumination

Side illumination involves directing light perpendicularly on either one side or on both sides of the subject's finger [1]. This method still allows an open device such that the user can see their finger. It effectively illuminates the veins by scattering within the finger tissue and by the diffusing property of the finger, enhancing contrast [2]. However, it can be susceptible to overexposure at the finger's edges, where light may reflect and scatter excessively, potentially hindering image quality in those regions [1].

As stated before in section I, there are side illumination setups on the market, that can perform finger vein recognition. The ZKTeco FPV10R [6] is the available system which performance could be used as a reference. Its performance can be observed in Figure 4 below. The vascular image as the result, is overexposed on the right edge of the finger. This problem is also present in commercially available products.

C. *Impact of illumination*

The impact of illumination on image quality is a crucial aspect that can significantly influence vein recognition. There exists a relationship between illumination methods, beam widths, and their consequences on image quality [5]. Key factors influencing this interaction include:

1) Direction of illumination
2) Light spread

The aim is to ensure that the obtained images show minimal overexposure.

Fig. 4: Vascular image captured with the ZKTeco "FPV10R"

1) Beam direction

An aspect to consider is that the orientation the the light source does not affect the image quality [5]. Research shows that vascular images are a result of indirect illumination, primarily through diffusion by the bone, which casts shadows on the finger's surface [2]. This principle suggests that side illumination can be possible, under the condition that the bone is illuminated.

2) Light spread

Wide beams of light pose challenges in capturing vascular patterns accurately. When the illumination is too broad, there is a higher chance of overexposure, where the intensity of light becomes too high for the camera to accurately capture the finer details of the vascular patterns [1]. In contrast, narrow beams of light offer several advantages in terms of image quality. They provide a concentrated and uniform intensity of illumination in the NIR spectrum, which is crucial for detecting and extracting vascular patterns with high clarity [5]. The reduced risk of overexposure is an effect associated with narrow beams, as excessive light intensity can wash out details and hinder vein recognition.

With the knowledge of optics, lighting methods and image quality, a solution to the main research question can be proposed. They show how the finger interacts with NIR light, and how side illumination is theoretically possible. While these topics were researched, the research on minimizing overexposure is still missing. The research question will cover this missing topic.

III. Method

This section gives a description of how the research questions are going to be answered. By describing the side illumination design, and by elaborating on experiments and evaluation. A successful implementation of side illumination can be achieved, with the results these experiments deliver.

A. Side illumination setup

This research revolves around a setup specifically designed for side illumination. This design aims to capture vascular images using a NIR-sensitive camera from beneath the finger, following the principles discussed in subsection II-B. In this setup, illuminators are strategically positioned on opposite sides of the finger. Notably, the distance between these illuminators is adjustable, accommodating variations in finger widths, recognizing the uniqueness of each individual's finger. This modular setup comprises a platform where the finger is comfortably positioned. An adjustable slit is incorporated into this platform, serving a crucial role in isolating the camera from the surrounding environment. It's imperative to tailor the slit width to match the finger's dimensions precisely, ensuring that extraneous light sources are effectively blocked out. This setup design is illustrated in Figure 5

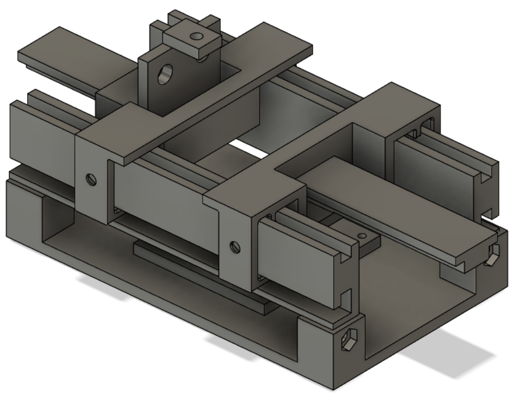


Fig. 5: Digital model of the illumination setup

The illuminators featured in this setup utilize the identical LEDs discussed in subsubsection III-B1. Each illuminator is precisely mounted perpendicular to the platform, ensuring that the light rays strike the finger at a right angle, effectively targeting the bone structure. What's noteworthy is the modular design of these illuminators, offering compatibility with all the illumination techniques detailed in subsection III-B. This design allows for interchangeability, providing the possibility to equip the experimental setup with various illumination techniques.

The illumination system operates under the control of MOSFETs, which receive two PWM signals generated by a Raspberry Pi to light the LED's. This pocket-sized computer serves as the central hub, connecting the camera and the MOSFETs. Its primary responsibility includes capturing vascular images and overseeing brightness control. It is important to note that while the Raspberry Pi effectively manages brightness, this control process remains manual. The exposure time of the camera, requires manual adjustment to achieve the desired results. This manual aspect offers a possibility for fine-tuning the imaging process according to specific conditions and objectives.

One key aspect worth elaborating on is the adaptability of this setup, is the modular nature. It allows for versatility in accommodating various finger sizes and shapes, acknowledging the inherent diversity among individuals. This adaptability is particularly valuable in order to capture consistent and accurate vascular patterns across a diverse user base. The design of this modular setup for side illumination is responsible for its effectiveness in capturing vascular images.

B. Illumination techniques

In accordance with the findings outlined in subsection II-C, the primary focus of this experiment is to achieve narrow light beams, thereby minimizing the issue of overexposure. Thereby achieving optimal results. There exist various methods for directing a light source. In order to achieve a narrow light beam, an adequate illuminator should be designed. An illuminator which utilizes the best-suited illumination technique. In this experimental context, an overview of five distinct techniques is given, all of which utilize reflection or absorption to narrow the light source. Within this section, all designed illuminators are 3d printed with black Acrylonitrile Butadiene Styrene (ABS) material.

1) Bare, narrow LED's

A straightforward approach to achieving focused illumination involves utilizing commercially available LED's with an inherently narrow transmission angle. In our case, the ”SFH4550” boasts a remarkable radiation angle of just 3 degrees, surpassing the narrowness of most other available LED's. However, examining the radiation graph in Figure 6, reveals that the radiation pattern is not perfectly flat. As it exhibits side lobes extending beyond 3 degrees. These side lobes are expected to generate undesirable halos around the central peak, an undesirable phenomenon that contradicts the specific application.

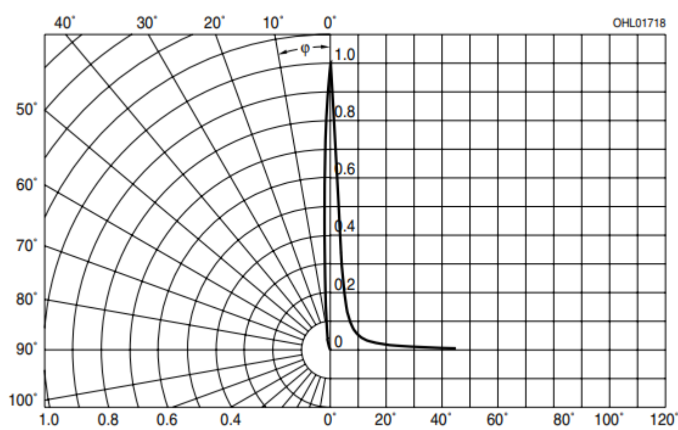
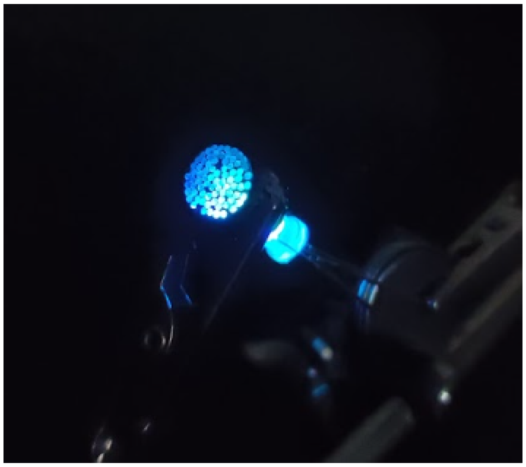


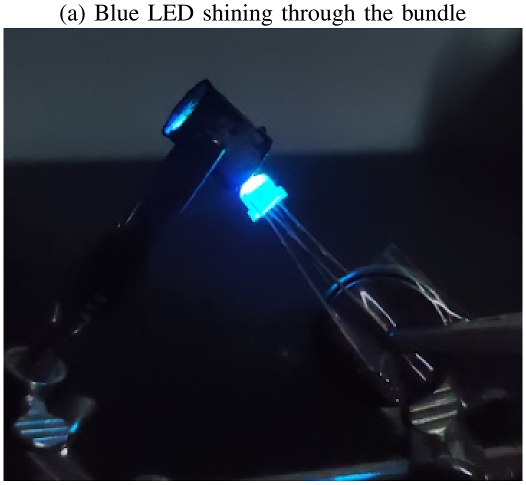
Fig. 6: Radiation pattern: SFH 4550 [7]

2) Optical fiber bundle

Optical fibers serve as an optimal medium for carrying light due to their internal reflective properties. This remarkable property enables the concentration of light beams into a single focused path. The core concept revolves around the assembly of a bundle of these optical fibers, effectively creating a conduit through which the light source can radiate. This principle is demonstrated in Figure 7. One of the challenges is the minimization of the spacing between individual fibers within the bundled arrangement. Achieving a compact inter-fiber gap is crucial in order to ensure that no dark spots will appear. Evenly spaced gaps are beneficial for efficient propagation of light throughout the assembly.



(a) Blue LED shining through the bundle



(b) Setup viewed from the side

Fig. 7: Optical fiber demonstration

Equally important is the need for perfectly flat and uniform surfaces at the entry and exit points of these optical fibers. This surface plays a role as the interface where light enters and escapes the fiber bundle. Even the slightest surface irregularities or roughness in the exiting surface can introduce disruptive scattering effects, causing the light to disperse in various directions.

To tackle this issue, it is essential to polish the surfaces. Polishing serves the purpose of refining the fiber bundle's exit surface, aiming o achieve the highest degree of smoothness achievable. Contributing significantly to the effectiveness of the illumination setup and the successful realization of the objective. Even minor imperfections in this critical area may result in subtle deviations in the emitted light.

3) Reflective tube

use of perspex tubes with reflective coatings effectively resolves the problem of surface scattering. These tubes, with a 8 mm diameter, feature an outer layer coated with reflective silver nitrate. The property of these tubes is that they guide light rays similarly to how optical fibers function, effectively concentrating the light beam along its direction. The cross section of the tube holder can be observed in Figure 8.

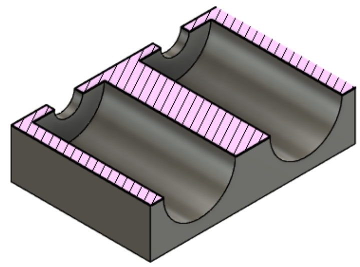


Fig. 8: Reflector holder model

The reflective coating extends seamlessly to the outer surface of the tube, ensuring a perfectly flat and uniformly reflective exterior. This approach eliminates the need for additional polishing. However, it's important to note that while this technique greatly minimizes surface scattering, it does not entirely eliminate the possibility of halos. Some light rays may still exit the tube at varying angles, causing a slight dispersion of light. Despite this, the overall reduction in scattering significantly enhances the precision and effectiveness of the illumination setup, making it a valuable option for the application.

4) Tube guides

This technique draws its inspiration from the principle of absorption, a well-established method utilized in previous vein acquisition devices. This illuminator is shown in Figure 9. Its core concept revolves around the absorption of the side lobes that appear in the radiation diagram of LED's. This strategy offers a straightforward yet highly effective means of achieving narrow light beams. Unlike some other methods, it's important to clarify that this process doesn't directly focus the light rays but rather negates the influence of side lobes.

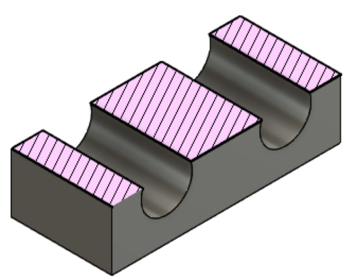


Fig. 9: Tube guides model

However, it's essential to consider that, theoretically, the potential for halos still exists. This possibility arises because light has a propensity to bend along the edges when it exits the tube. This phenomenon is commonly referred to as the "edge effect." While this method significantly reduces the occurrence of unwanted scattering and side lobes, it's important to acknowledge the potential for subtle light dispersion along the tube's edges, which may lead to the formation of halos.

5) Tapered guides

This approach draws inspiration from the tube guides mentioned in subsubsection III-B4. However, it introduces a noteworthy departure in the form of tapered guides characterized by their conical tube design. Which can be observed in Figure 10. As the tubes progress toward the guide's exit, they are gradually getting narrow, resulting in a finer, more compact emitted light beam. It's important to emphasize that, while this method narrows the light beam, it still doesn't actively concentrate the light rays.

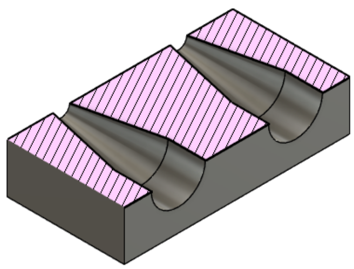


Fig. 10: Tapered guides model

The primary rationale behind this tapered design is to mitigate the spread of light attributed to the edge effect. This effect, which causes light to bend or disperse along the tube's edges, is responsible for the potential light spread and, subsequently, the formation of halos. Similar to the tube guides discussed earlier, these tapered guides are also crafted using 3D printing technology, utilizing the same material as the tube guides. This shared material facilitates the creation of the conical shape with relative ease.

C. Evaluation steps

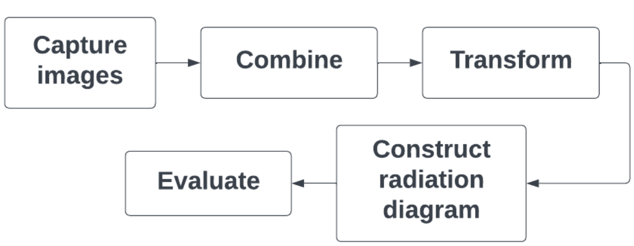


Fig. 11: Flow diagram: evaluation steps

To select the most suitable illumination technique, each one must undergo evaluation. This evaluation process involves the creation of spectral diagrams, as depicted in Figure 6. These diagrams visualize the radiation pattern of the chosen technique, and are able to quantify spread. The flow diagram in Figure 11, shows the necessary steps to evaluate an illumination technique.

1) Capturing

The setup for capturing such radation patterns, inlcudes:

1) A light source equipped with the chosen technique.
2) A checkerboard canvas.
3) A NIR-sensitive camera.

The capturing setup and its components can be observed in Figure 12. Within this setup, the light source directs its beams onto the canvas positioned perpendicular to it. As the light source radiates, it projects its distinct radiation pattern onto the canvas surface. An NIR-sensitive camera, situated at an angle relative to the canvas, captures this pattern. However, due to the camera's angled perspective, the resulting image becomes distorted.

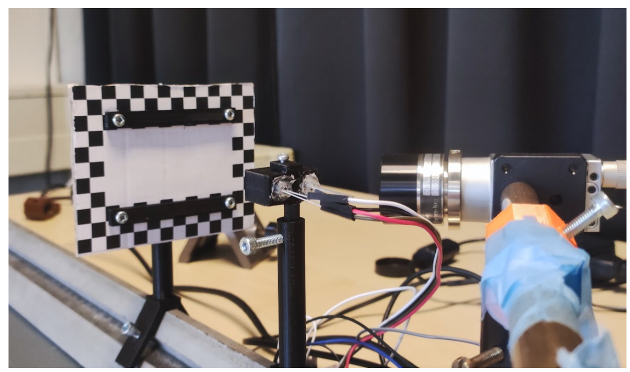


Fig. 12: Evaluation setup

When capturing radiation patterns, it's crucial to vary the shutter speed, which is the duration that the camera sensor is exposed to light [8]. This variation is essential as it reveals subtle details that may remain hidden at lower shutter speeds, such as faint halos. At high shutter speeds, intense areas can become overexposed, an effect to be avoided. The ideal radiation pattern exhibits balanced intensity levels, ensuring nothing is lost to saturation.

2) Combining

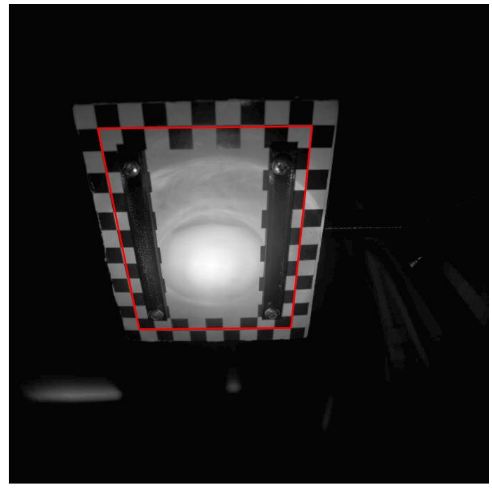
To construct this optimal radiation pattern, images taken at different shutter speeds are combined in MATLAB. This process, begins at a base shutter time that gradually increases, with each iteration doubling the exposure time. High exposure will capture faint halos and details, from which a complete radiation pattern can be constructed, capturing both weak and strong intensities. The procedure in combining these images is to use masks. The image with the lowest shutter speed (highest shutter time) will contain faint details and a saturated area. A mask takes the saturated areas, and replaces them with an image captured at a lower shutter time. After iterations and proper scaling, a radiation pattern is constructed.

3) Transformation

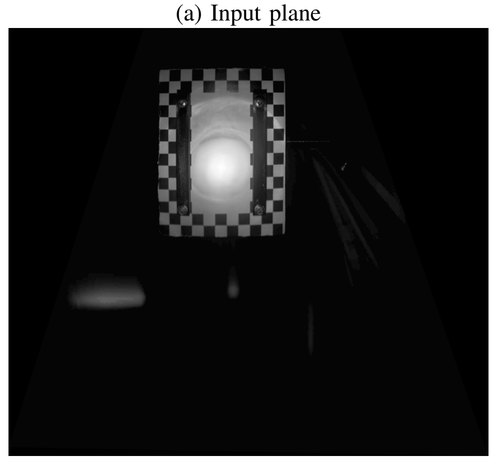
Since the camera is oriented at an angle towards the canvas, resulting radiation patterns will be distorted. To obtain an accurate representation of the radiation pattern, it is essential to apply image correction. This correction technique ensures that the final pattern closely approximates what one would observe if the camera were ideally aligned perpendicular to the canvas surface. The correction process is executed in MATLAB through projective transformation [9], a technique capable of transform a pitched image into a flat plane. This transformation allows for the correction of distortions caused by perspective variations.

To achieve this, it calculates the orientation of a chosen plane within the image by taking a rectangular area within the image as the reference for determining this orientation [9]. The corrected image is the result of applying this calculated orientation to the entire image. In essence, this procedure rectifies the pitched plane by aligning its points with a normal, flat plane. As a result of this planar transformation, straight lines within the image remain straight. Note that parallel lines converge towards vanishing points, which could either fall within or outside the image frame.

In Figure 13, projective transformation is shown in practice, demonstrating its application. As can be seen, Figure 13a shows a deformed red rectangle, which serves as the input plane for the transformation. When examining both Figure 13a and Figure Figure 13b, it is important to consider the distinctive shape of the checkerboard pattern, both before and after the transformation process. This comparison advocates the effectiveness of projective transformation in rectifying geometric deformations. It can be observed that the tiles in the corrected checkerboard are perfectly square.



(a) Input plane



(b) Corrected image

Fig. 13: Projective transformation result

4) Constructing radiation diagrams

The radiation pattern is visualized by examining pixel values along two orthogonal axis. With the centre of the radiation pattern being the origin of those axis. This origin marks the 0 degree point. The distance between the origin and the nth pixel left or right from the origin is proportional to the angle. The horizontal axis of this diagram can be constructed from the distance of the nth pixel. Finally, the radiation diagram can be created by plotting every nth pixel value and their corresponding angle.

5) Evaluation table

Radiation pattern can be characterized by their 50% value [10]. This is the angle for which the intensity is halved from its peak value. Each radiation pattern has two 50% values, since radiation patterns are symmetric. The angle between those values can be called spread. In this scenario is the measure of spread a metric in performance. The decrease or increase in spread is calculated by examining the 50% values:

$$Change = \frac{50\%_{chosen} - 50\%_{LED}}{50\%_{LED}}$$

In order to distinguish illumination techniques based on performance, a figure of merit needs to be introduced. The figure of merit in question considers spread and light attenuation as primary factors. A well performing technique should decrease spread without attenuating the intensity. By taking the ratio between the peak value of the chosen technique and bare LED's, attenuation can be described. The figure of merit should take the product between spread reduction and the peak ratio, in order to quantify the performance. In this case is the best perfoming technique, the one with the lowest (negative) figure of merit.

$$FoM = Change * \frac{Peak_{chosen}}{Peak_{LED}}$$

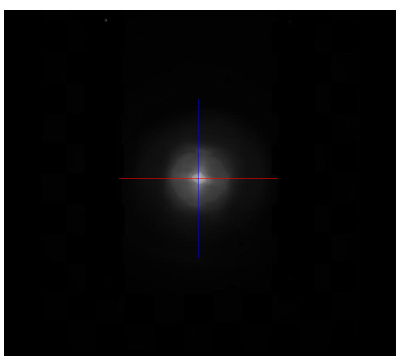
In order to demonstrate the possibility of a side illumination setup with minimized overexposure, a suited light source should be chosen and implemented. The highest ranking illumination technique that the evaluation steps showed to be, will be implemented in the illumination setup. Built according to the methodology described in subsection III-A. Its resulting vascular image will answer the main research question. Moreover, the systems performance can be compared with a product performance shown in Figure 4.

IV. Results

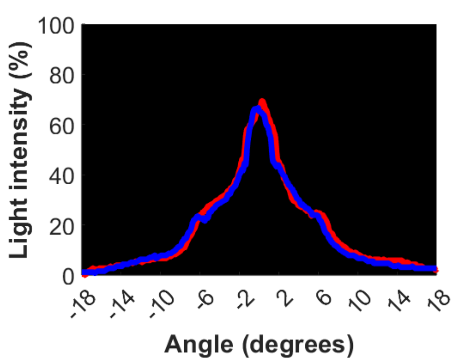
This section focuses on the outcomes of the image correction process, and the analysis of radiation patterns detailed in subsection III-C. Moreover, an evaluation table is constructed where radiation patterns can metrically be compared by a figure of merit. Finally, the most suitable illumination technique is chosen to be compared with bare LED's in the illumination setup.

A. Radiation patterns

The evaluation setup, as described in subsection III-A, makes constructing radiation patterns possible. For each radiation pattern, its radiation peak was taken as a reference point marked by a cross, as shown in Figure 14a. The pixel values of individual pixels along both the horizontal and vertical axis were examined. These intensity values were plotted against the respective angles, resulting in a radiation pattern. This systematic approach allowed for analysis of the radiation patterns, offering a graphical representation across various angles from the reference point. The diagrams in this section are enlarged and simplified for the sake of readability. More detailed radiation patterns can be found in Appendix A and B. As stated before in subsubsection III-C5, promising radiation diagrams must be narrow and should have a high peak value relative to bare LED's. It can be observed that Figure 15b shows increase in spread, while Figure 16b shows attenuation in amplitude.



(a) Selected area



(b) Radiation pattern. Red: horizontal intensity. Blue: vertical intensity

Fig. 14: Evaluation results, a bare LED

B. Evaluation table

Table I is filled with radiation pattern characteristics mentioned in section subsection III-C. The 50% angle gives a measure of spread. While a spread increase or decrease compared to bare LED's is given by the change formula in subsubsection III-C5. A decrease in spread is preferable in these results. Peak values are compared using a peak ratio. The optimal peak ratio in this scenario is equal to one. The figure of merit can be calculated by taking the product of the spread and peak ratio. Since a high decrease in spread and low attenuation are desired results, the best-performing illumination technique must have the lowest figure of merit.

TABLE I: Evaluation table

	50% Angle	Change in spread	Peak ratio	F.o.M.
Tapered guide	2.1°	-30%	0.94	-28.20
Reflective tube	2.0°	-33%	0.48	-15.84
Tube guide	2.6°	-13%	0.96	-12.48
Bare LED	3°	0%	1	0
Optical fiber	18.0°	500%	0.49	245

C. Side illumination setup

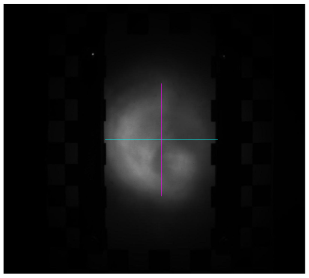
This part covers the performance of the side illumination setup under two distinct scenarios: one utilizing bare LED's and the other incorporating the tapered illumination technique elaborated in subsubsection III-B5. Notably, this particular technique has displayed significant promise, with the lowest figure of merit in Table I. The results of these scenarios are presented in Figure 19. By visually examining the reduction in white areas, the effectiveness of the tapered illumination technique can be confirmed.

V. Discussion

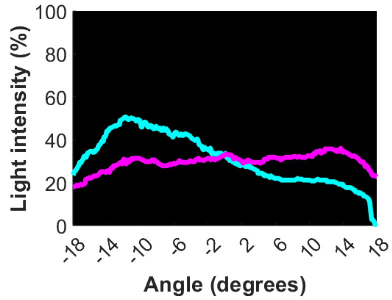
Table I provides a ranking of the illumination techniques based on their performance. As stated in section subsubsection III-C5, the illumination setup benefits from the technique with the lowest figure of merit. Consequently, the tapered guides secured the highest score in the evaluation table, providing narrow beams.

A. Optical fiber bundle

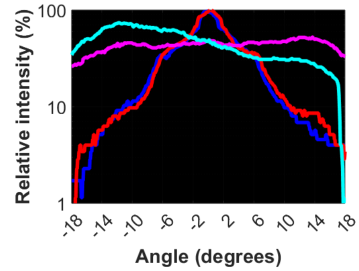
The technique that performed the poorest, was the optical fiber bundle. As clearly shown in Figure 15b, this method diffuses light across a wide area. To avoid this diffusion effect, it is crucial to achieve an ideally flat surface from which light escapes. Any surface irregularities can induce light scattering in different directions, as discussed in subsubsection III-B1. Irregularities can be evened out by polishing the fibers. Despite these efforts, the diffusive effect occurred even with polished fiber bundles. Achieving a sufficiently flat surface requires specialized polishing equipment. Figure 15c shows how this technique increases spread and decreases intensity, contributing to its lower rank in the evaluation table.



(a) Selected area

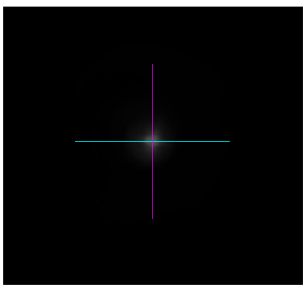


(b) Radiation pattern. Cyan: horizontal intensity. Magenta: vertical intensity

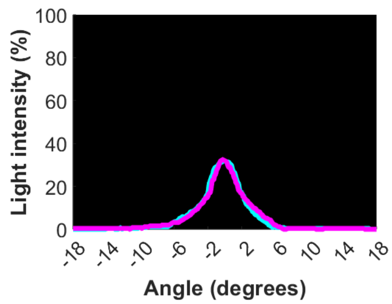


(c) Radiation pattern relative to a bare LED in log scale. Red/bue: bare LED. Cyan/magenta: optical fiber

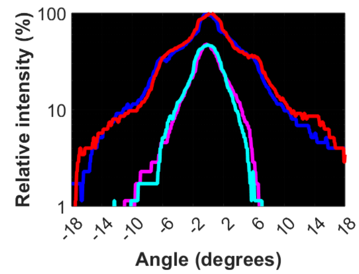
Fig. 15: Evaluation results, optical fiber bundle



(a) Selected area

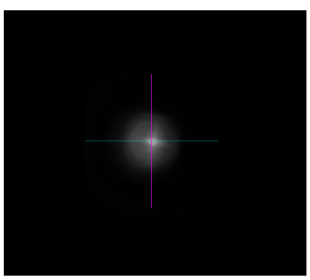


(b) Radiation pattern. Cyan: horizontal intensity. Magenta: vertical intensity

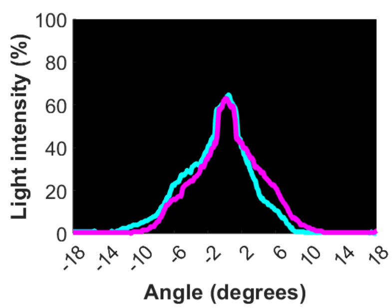


(c) Radiation pattern relative to a bare LED in log scale. Red/bue: bare LED. Cyan/magenta: reflective guide

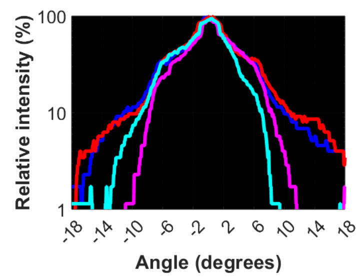
Fig. 16: Evaluation results, reflective tube guides



(a) Selected area

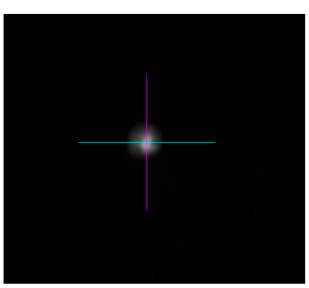


(b) Radiation pattern. Cyan: horizontal intensity. Magenta: vertical intensity

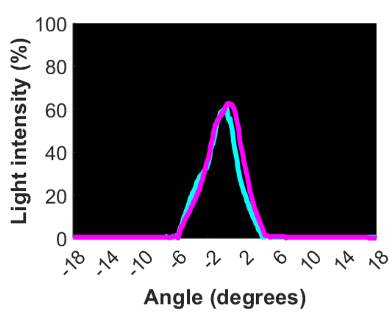


(c) Radiation pattern relative to a bare LED in log scale. Red/bue: bare LED. Cyan/magenta: tube guide

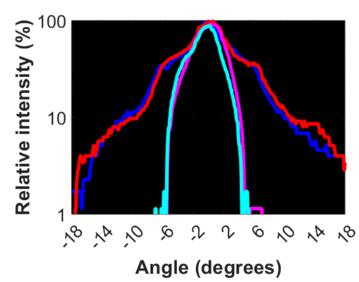
Fig. 17: Evaluation results, tube guides



(a) Selected area

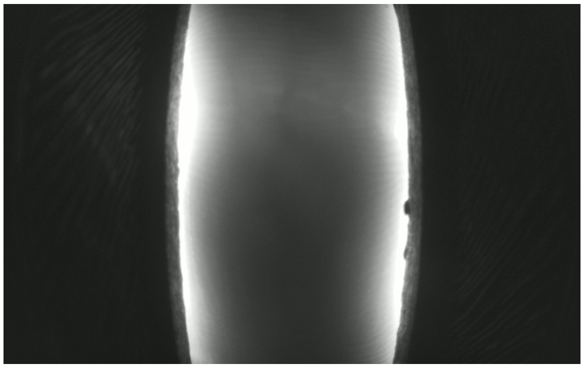


(b) Radiation pattern. Cyan: horizontal intensity. Magenta: vertical intensity

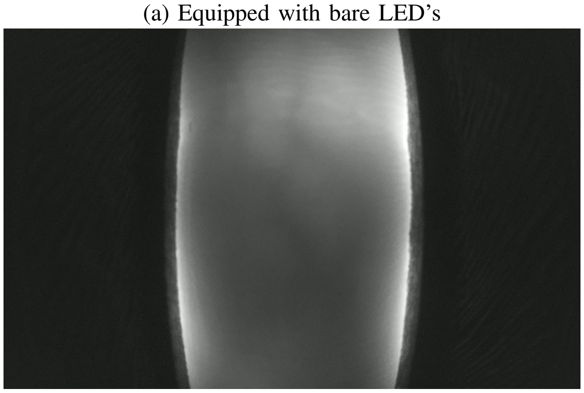


(c) Radiation pattern relative to a bare LED in log scale. Red/bue: bare LED. Cyan/magenta: tapered guide

Fig. 18: Evaluation results, tapered guides



(a) Equipped with bare LED's



(b) Equipped with tapered guides

Fig. 19: Side illumination applied

B. Bare LED's

As stated in subsubsection III-B1, the bare LED's were expected to have a radiation angle of 3 degrees. This radiation angle came out as a result of its radiation pattern, shown in Figure 14b and Table I. Notably, Figure Figure 14b shows an increase in the side lobes of the pattern, particularly below the 50% intensity mark. Despite the LED's specified rating of 3 degrees, there are rays present that have a wider radiation angle. These rays contribute to the occurrence of overexposed regions surrounding the finger.

C. Reflective tube

After examining Figure 16c, it can be observed that the reflector's peak value is significantly lower than that of a bear LED. This effect is caused by absorption, occurring within the reflective tube. The absorption takes place within the perspex material, which has a reflective coating applied on its exterior surface. It is important to note that this reflection occurs after the light has radiated through the perspex layer. Nevertheless, Figure 12 indicates a reduction in the 50% value, while Figure 16b provides visual evidence of this phenomenon.

D. Tube guides

Figure 17b illustrates how the tube guides absorb the side lobes emitted by the LED. This absorption is advantageous, particularly when the goal is to generate narrow beams. Notably, it results in the absorption of the lowest 10% of the rays, as can be confirmed in Figure 17c.

E. Tapered guides

Given the ranking position of the tapered guide technique in Table I, it has been implemented in the side illumination setup. Its result is depicted in Figure 18. The tapered guide scored high because it showed a reduction in spread by 30%, while maintaining a high peak intensity.

F. Side illumination setup

The vascular images in Figure 19, show how tapered guides perform against bare LED's in practice. Figure 19b demonstrates a more uniform diffusion of light, while Figure 19a highlights overexposed areas around the edges of the finger. These observations are made through visual evaluation. Alternatively, the performance of the tapered guides can be measured when performing vein detection. Vein detection will be expected to improve with tapered guides since Figure 19b shows less dark and also overexposed areas on the finger. Such areas are the main difference between vascular images shown in Figure 19.

VI. Conclusion

The main objective is to design a side illumination setup with adequate lighting, since the light source affects the vascular image quality. To achieve a functioning illumination setup, the light source must be able to reduce overexposure in vascular imaging. The sub-question that covers this problem is, *which lighting design can minimize overexposure during side illumination?*. subsection II-C stated that by creating narrow beams, the amount of reflection and thus overexposure will reduce. This research focused on five different illumination techniques, to achieve narrow beams. Their performance is listed in Table I, with the tapered guide design ranked as the best performing. Which suggests an answer that the tapered guide the best candidate out of five different techniques is.

The next question will be on how side illumination can be applied in practice. subsection III-A proposed a modular design as the solution. With adjustable parameters, the illumination device can be tweaked to fit anyone's finger anatomy. With this design and the chosen illumination technique, a functioning illumination setup is built that could capture vascular images with reduced saturation compared to the reference in Figure 4. The decrease in radiation spread and its effect on saturation can be observed in Figure 19b and Figure 19a. Figure 19 confirms that the setup described in subsection III-A, answers the research question: *it is possible to create a side illumination setup, while minimizing overexposure*.

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Appendix A
Detailed radiation patterns

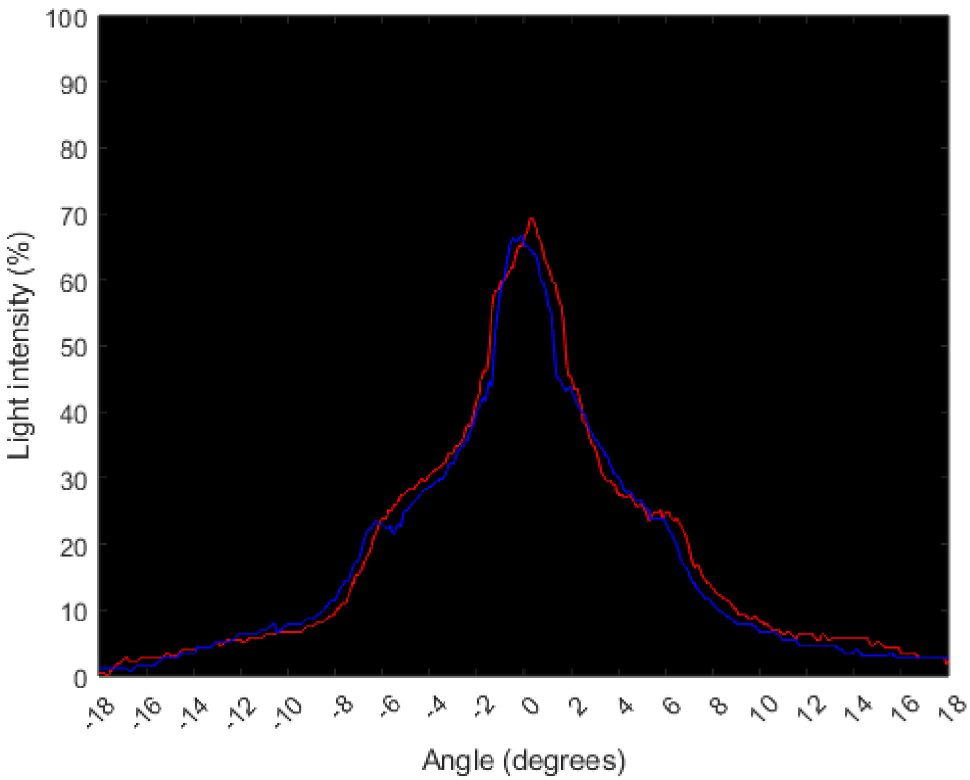

Fig. 20: Radiation pattern, LED. Red: horizontal intensity. Blue: vertical intensity, Figure 14b in high detail

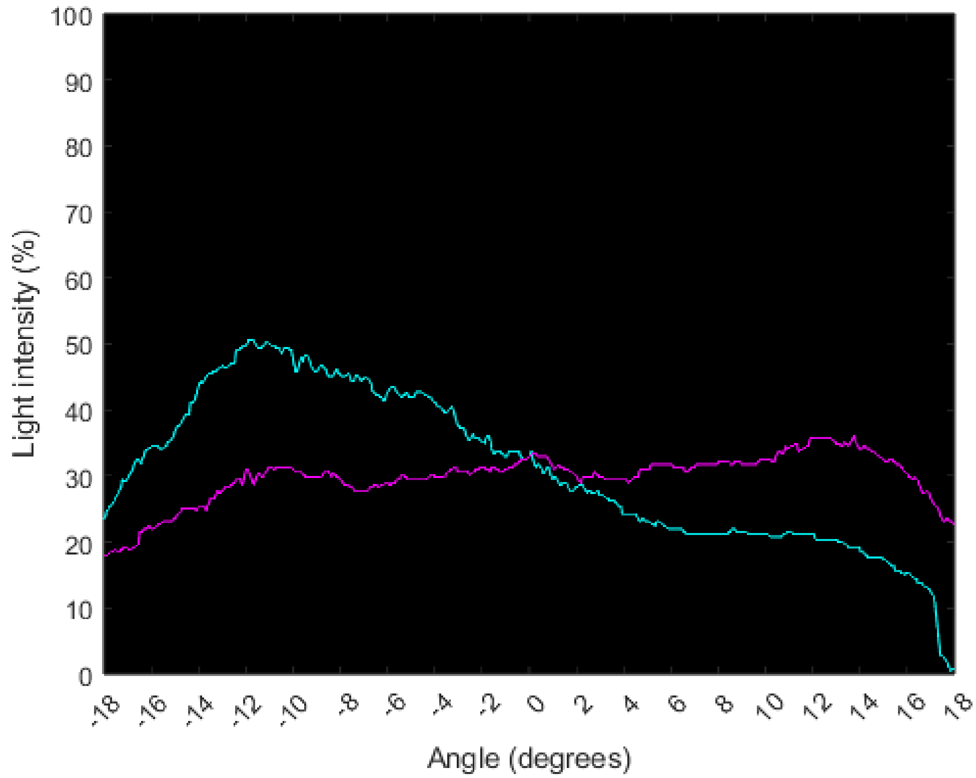

Fig. 21: Radiation pattern, fiber. Red: horizontal intensity. Blue: vertical intensity, Figure 15b in detail

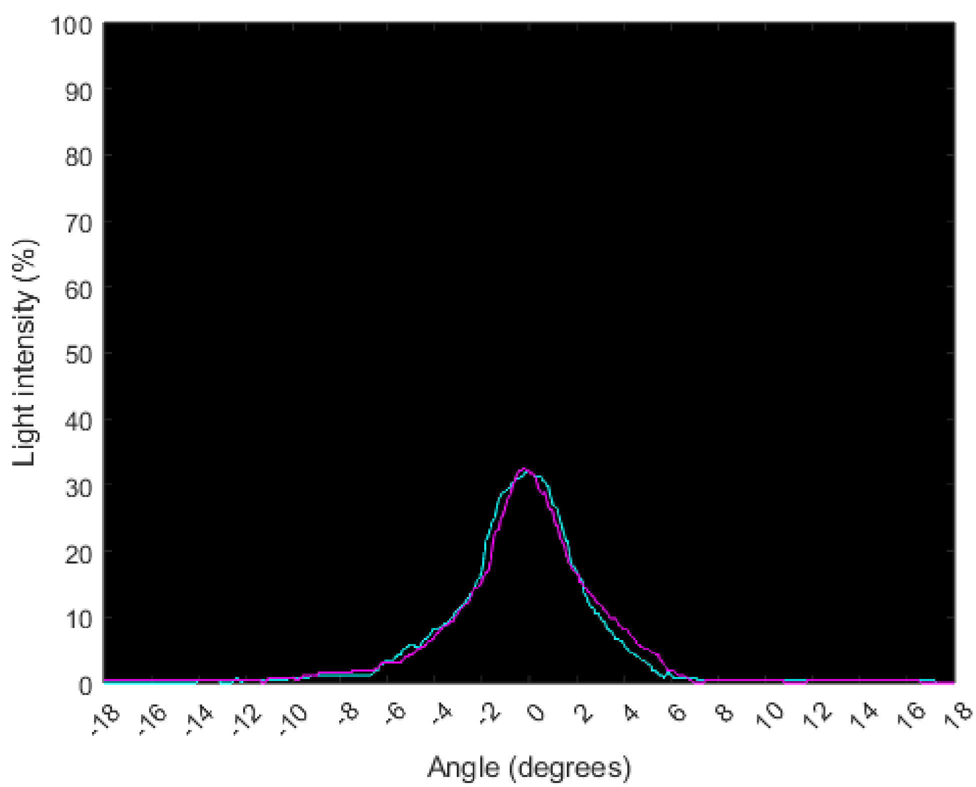

Fig. 22: Radiation pattern, reflector. Red: horizontal intensity. Blue: vertical intensity, Figure 16b in detail

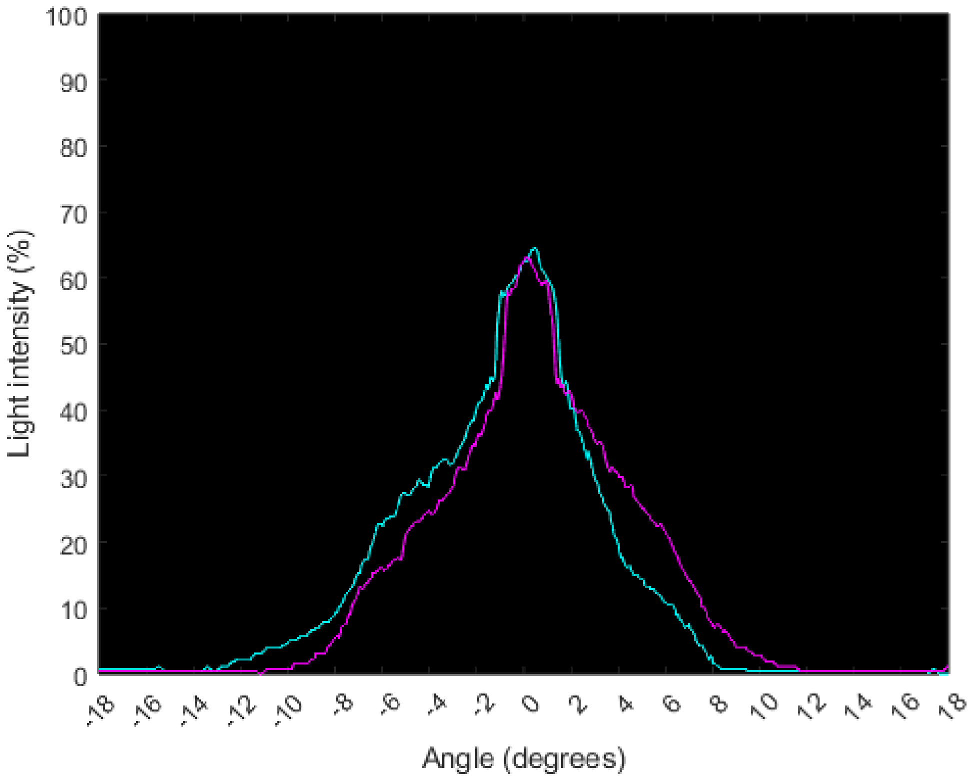

Fig. 23: Radiation pattern, tube. Red: horizontal intensity. Blue: vertical intensity, Figure 17b in detail

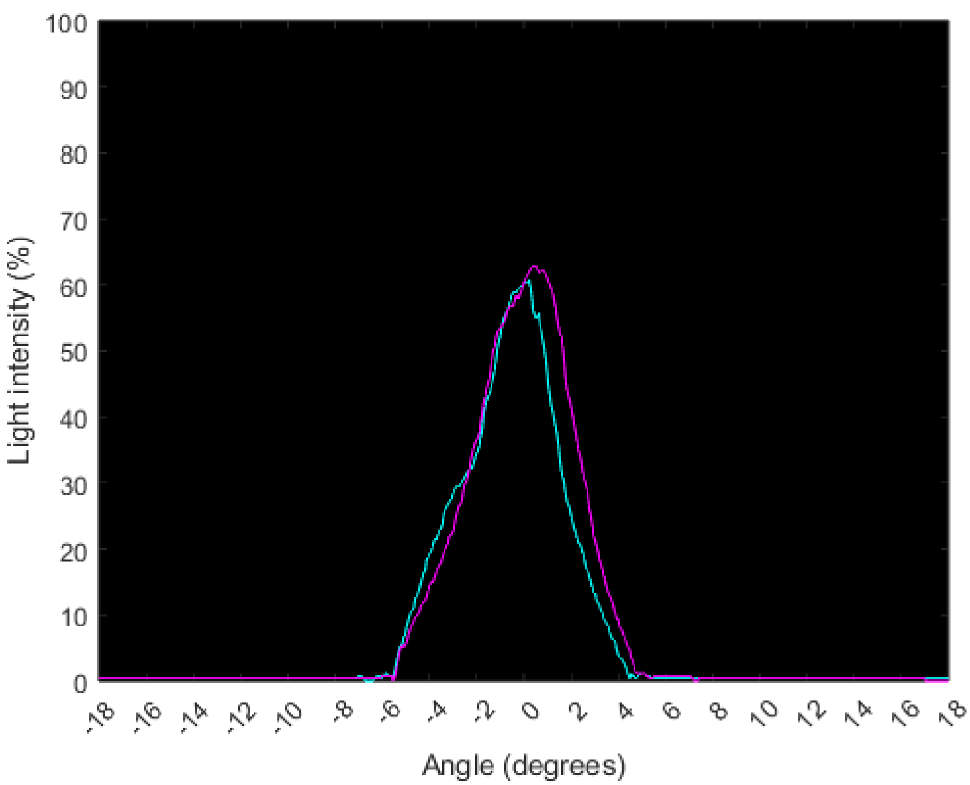

Fig. 24: Radiation pattern, tapered. Red: horizontal intensity. Blue: vertical intensity, Figure 18b in detail

Appendix B
Detailed relative plots

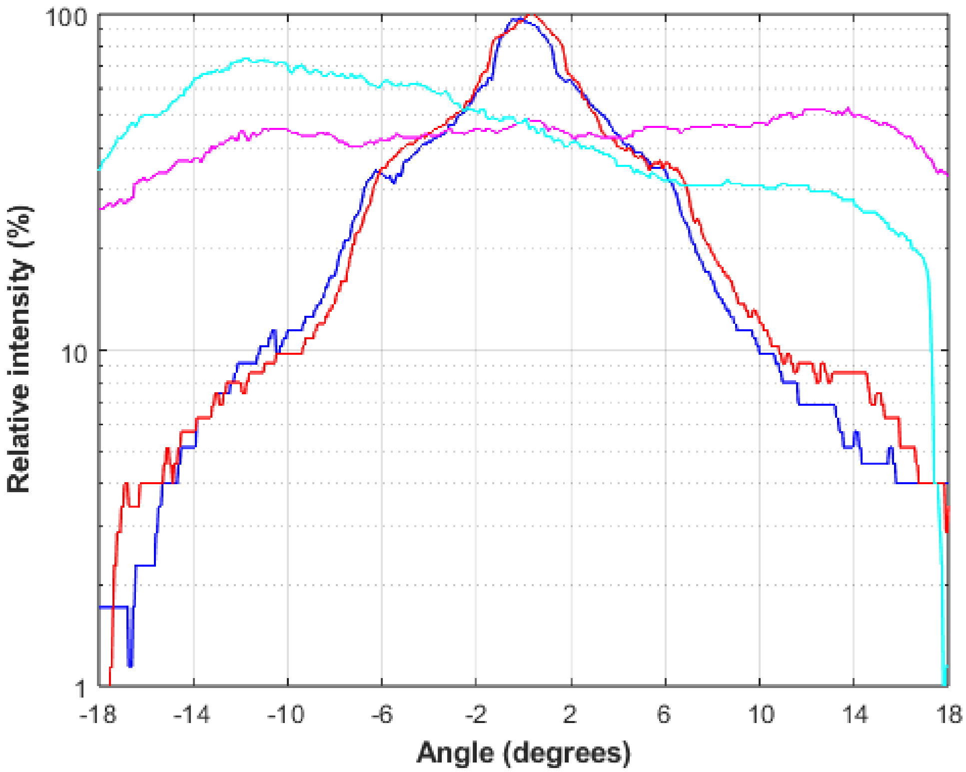

Fig. 25: Fiber pattern relative to bare LED. Figure 15c in detail

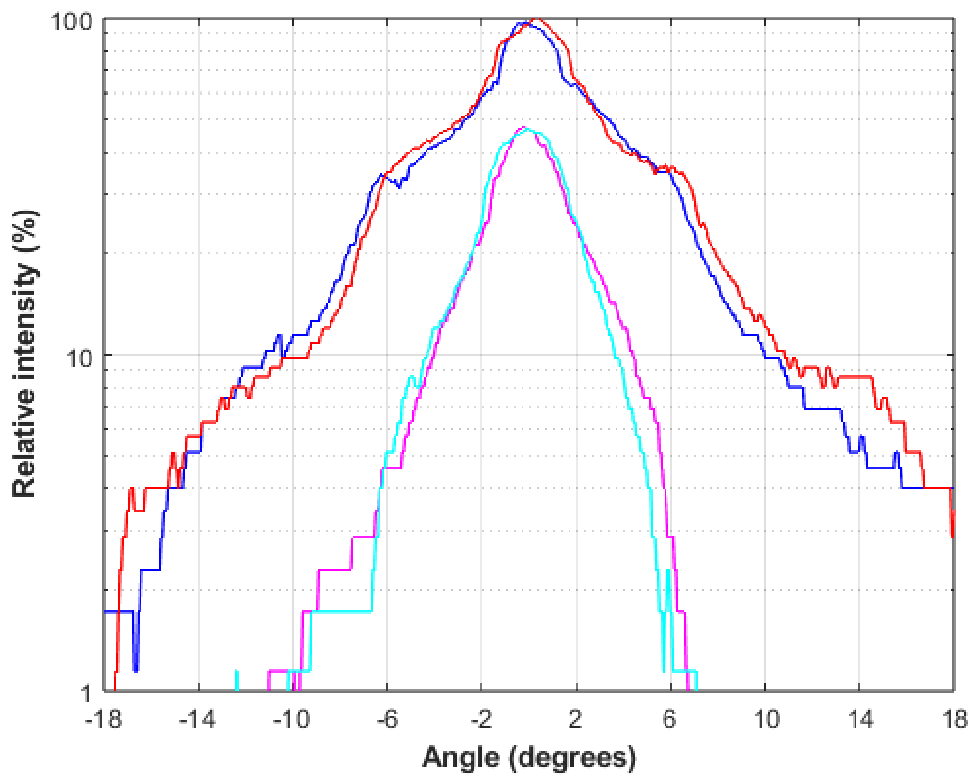

Fig. 26: Reflector pattern relative to bare LED. Figure 16c in detail

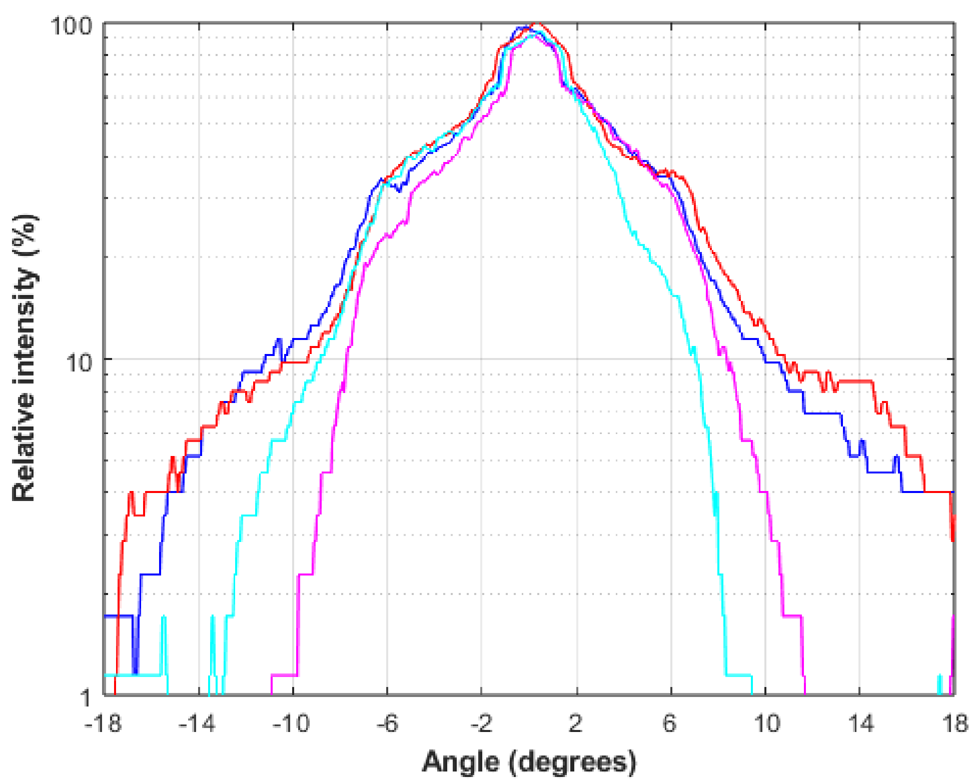

Fig. 27: Tube pattern relative to bare LED. Figure 17c in detail

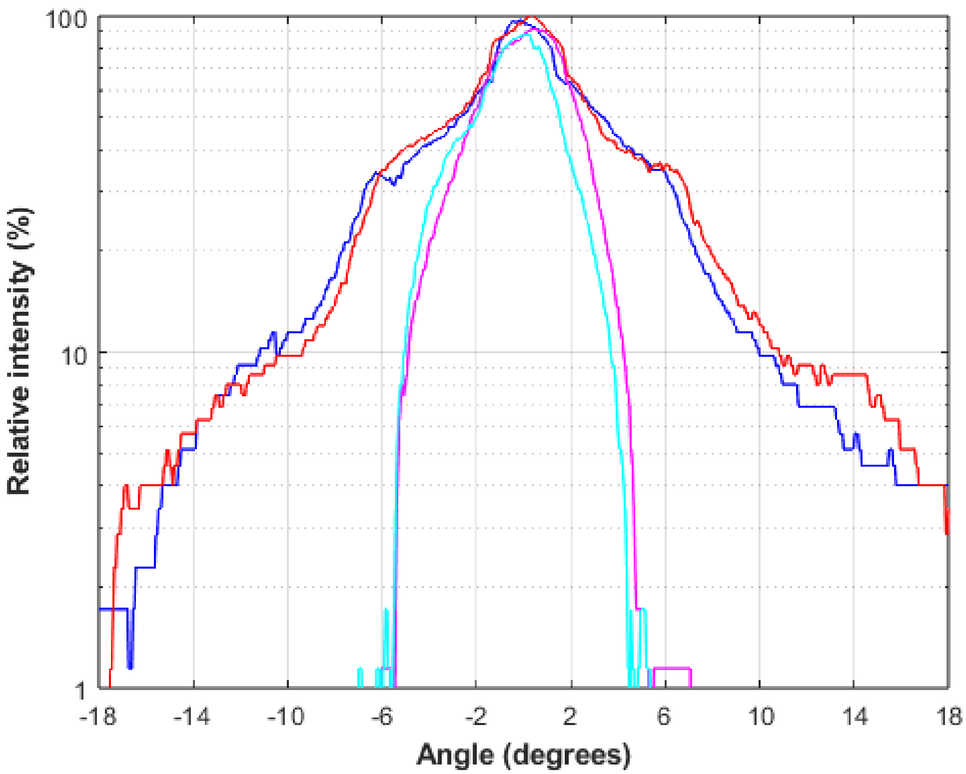

Fig. 28: Tapered pattern relative to bare LED. Figure 18c in detail