Simulation of the parameters of the acrylic and specular light pipe for transmitting light radiation of the LED matrix

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Abstract. In this article, we simulated the parameters of an acrylic and specular light pipe to transmit radiation from the LED matrix. The results of the experiment can be estimated using the dependence of the light flux on the number of reflections in the specular light pipe. Evaluation was conducted in the software package “Mathcad”. The possibility of providing illumination from 6 to 30 lx using the system of transportation of artificial light of roads / streets / squares depends on the class of the object. The study of the transmission of light through a specular and acrylic light pipe has shown that under equal conditions of light transport (the same power, the same aperture, the equal length of the light pipe, the same diameter of the light pipe), the acrylic fiber has the advantage. Losses using acrylic light pipe of 2000 mm are 24% whereas using specular light pipe they are 45%. However, if there is no limitation in the diameter of the light pipe, then it is preferable to use a specular one. For example, at 150 mm the losses are no more than 13%, which is not achieved with an acrylic light pipe even with a diameter of 10 mm, since when the radiation aperture is kept, a reduction in diameter leads to an increase of the interaction of the radiation with the walls of the acrylic rod and increase of the optical path.

1. Introduction
The system of transportation of artificial light (STAL) will significantly reduce maintenance costs for street lighting, since the radiation source is at a height of no more than 1-2 meters. It does not require a crew to call at height, as well as the life of LED arrays of about 100,000 against DRL lamps is 10,000 hours, which allows replacement of the source not once every 2.7 years, but once every 27 years (provided that the radiation source is operating 10 hours a day). From the results of the experiment, it was expected that radiation losses in the specular light pipe would not exceed 20%, and even less in acrylic light pipe. And with increasing diameter of the specular light pipe, the losses would decrease as the number of reflections would decrease. This would make it possible to efficiently operate the STAL system for lighting roads / streets / squares [1, 10].

2. Materials and methods
The radiation of a light source (LED matrix) with the help of an optical concentrator system is installed into a light pipe representing a hollow cylinder with a specular-like inner surface or an acrylic rod. The light pipe is located inside the post. After being transported by the light pipe, the radiation falls on the
lens, which forms the necessary light intensity curve (Figure 1).

A diode matrix (Figure 2) was used as a radiation source. SMJD-3V16W1P3 (Table 1).

For the manufacture of a specular light pipe, an anodized sheet of Miro 44270 GP from Alanod was used with 95% specular and 6% diffuse reflection.

An acrylic rod 30 mm in diameter and 2000 mm long was used as an acrylic light pipe.

Table 1. Characteristics of the diode matrix SMJD-3V16W1P3.

| Characteristic                | Value |
|------------------------------|-------|
| Luminous flux, lm            | 1350-1450 |
| Power, W                     | 16    |
| Light return, lm / W         | ~90   |
| Color temperature, K         | 5600  |
| Color rendition index, CRI, Ra| 80    |
| Radiation angle, °           | 120   |

Connecting wires were fixed to the diode matrix with the help of a soldering iron using solder. With the help of pliers and a screwdriver, a coupling plug was attached to the connecting wires. For usability of a matrix the platform was cut from MDF to fasten the matrix (Figure 2).

Three tubes 1250 mm long and 70 mm in diameter equal to the diameter of the substrate of LEDs were manufactured from an aluminum sheet (anodized specular Miro 44270 GP). Next, the tubes were connected to a specular light pipe with a length of 3600 mm (Figure 4).
Next, the measurement of the luminous flux of the matrix was carried out using a luxmeter with the lights turned off (Figure 5).

Knowing the area of the sensitive meter of the luxmeter and the measurement result, one can determine the luminous flux of the matrix:

\[ t = 0.02 \cdot 0.02 \cdot \pi \cdot 360000 \cdot 3 = 1357 \text{lm} \]

The measurement shows that the luminous flux of the matrix is 1357 lm, which corresponds to the declared characteristics in table 1.

Then the platform with the matrix was installed in the specular light pipe so that the maximum amount of light flux was directed into the light pipe. The luminous flux was measured at the output end of the specular light pipe (Figure 6).

Measurements show 10,000 lx, with the light pipe end face area of 0.0038 m² is 38 lm(Figure 7).

Further, at a distance of 4400 mm, the measurement of illumination at the brightest point was carried out (Figure 8).

Measurement of the luminous flux was carried out using specular light pipes of different diameters: 70 mm; 100 mm; 150 mm.
In order to direct the maximum amount of luminous flux into an acrylic light pipe, a conical mirror concentrator with an arbitrary inclination of the generatrix was used. Measurements were also carried out on the output end of the acrylic rod and at a distance of 2000 mm from the end.

3. Discussion
The results of measurements of the light flux of the diode matrix in the framework of the experiment during transportation using a specular and acrylic light pipe are summarized in Table 2.

| Diameter of the specular light pipe, mm | Light pipe length, mm | Light flux at the end of the light pipe, lm | Illumination at the end of the light pipe, Lx | Illumination at a distance of 4400 mm, Lx |
|----------------------------------------|-----------------------|-------------------------------------------|--------------------------------------------|----------------------------------------|
| 70                                     | 3600                  | 38                                        | 10000                                      | 12                                     |
| 100                                    | 3600                  | 188                                       | 24000                                      | 19                                     |
| 150                                    | 3600                  | 387.2                                     | 22000                                      | 22                                     |

| Diameter of the acrylic light pipe, mm | Light pipe length, mm | Light flux at the end of the light pipe, lm | Illumination at the end of the light pipe, Lx | Illumination at a distance of 2000 mm |
|----------------------------------------|-----------------------|-------------------------------------------|--------------------------------------------|----------------------------------------|
| 30                                     | 2000                  | 26                                        | 37000                                      | 12                                     |

The results of the experiment, as expected, show that with increasing diameter of the specular light pipe, the amount of light flux increases, which affects the growth of illumination at an equidistant point.

The results of the experiment can be estimated using the dependence of the light flux on the number of reflections in the specular light pipe.

Evaluation was conducted in the software package “Mathcad”. The range of $\alpha$ radiation angles of the diode matrix was set from 0 to 60° (Figure 9).

Figure 9 shows that the smaller the aperture of radiation propagation, the smaller the number of reflections, because from the MNP triangle it is seen that the longer the MN, the less reflections the radiation in the specular light pipe will experience. It is possible to obtain the extension of MN in two ways: to reduce the radiation aperture of the diode matrix and to increase the diameter of the specular light pipe.

For a diameter of 70 mm, the following lengths MN are obtained, depending on the angle of incidence $\alpha$:

$$A(\alpha) = \frac{0.07}{\tan \left( \frac{\alpha \cdot \pi}{180} \right)}$$

$A(\alpha)=0.8; 0.666; 0.57; 0.498;…$

From the calculations it is clear that with an increase in the angle of incidence $\alpha$, the length of the segment MN is reduced.
The number of reflections in a light pipe length of 3600 mm increases:

\[ B(a) = \frac{3.6}{A(a)} \]

\( B(a) = 4.499; 5.405; 6.315; 7.228; \ldots \)

Then the luminous flux at the output end of the specular light pipe:

\[ t_i = \sum_{\text{V}_i} \cdot 0.9 \cdot 0.9 = 110.834 lm. \]

The reflection coefficient of the material was taken at 0.89, because from the data of the manufacturing company Alanod it follows that the total reflectivity of the material is 95% (for angles of 60° - 91%), of which 6% diffuses and, practically, is lost in a long mirror shaft.

For light pipes with a diameter of 100 mm and 150 mm, we have:

\[ t_2 = \sum_{\text{V}_i} = 216.155 lm \]

\[ t_3 = \sum_{\text{V}_i} = 336.349 lm. \]

The calculation results are listed in table 3.

| Diameter of the specular light pipe, mm | Maximum number of reflections | Light flow by calculation, lm | Difference of calculated and experimental data, % |
|--------------------------------------|-------------------------------|----------------------------|-----------------------------------------------|
| 70                                   | 89                           | 136.8                      | 257                                           |
| 100                                  | 51                           | 216                        | 14                                            |
| 150                                  | 41                           | 336                        | 13                                            |

From the calculations it can be seen that the dependence of the luminous flux on the diameter of the specular light pipe is almost linear, so: 100 mm / 70 mm = 1.43; 216 lm / 136.8 lm = 1.5; 150 mm / 100 mm = 1.5; 336 lm / 216 lm = 1.55.

That is, with an increase in diameter, the luminous flux also grows almost linearly, knowing the ratio of the diameter of the light pipes and the luminous flux of one of them, you can estimate the luminous flux of a specular light pipe of a different diameter.

4. Analysis of calculations

Analyzing the results of calculations and experimental data, it can be seen that for diameters of 100 mm and 150 mm, the difference in luminous flux at the light pipe end is not more than 14%, which is associated with an error of a luxmeter of about 10%. This indicates a satisfactory consistency of calculations and experimental results for these diameters. For a light pipe diameter of 70 mm, the difference in the calculated light flux from the experimental one is more than 257%. The explanation for this fact is that the measurement of the luminous flux for a given diameter was carried out last, the specular material in the manufacture of 100 and 150 mm of the light pipe got scratches, small dents. Because of the twist, the shape of the inner surface was in places not cylindrical, but elliptical. The joints of the tube connections made greater losses than for 100 and 150 mm tubes, as part of the luminous flux “spotted” at the input end of the specular light pipe, which was not observed for 100 and 150 mm tubes [1].

If we estimate the loss of the specular light pipe as the ratio of the light flux of the diode matrix to the light flux at the output end of the specular light pipe, we obtain: for 70 mm: 1357 lm / 38 lm = 35.7; for 100 mm: 1357 lm / 188 lm = 7.2; for 150 mm: 1357 lm / 387 lm = 3.5.
It follows that the minimum loss in the experiment was about 71% with a light pipe diameter of 150 mm, which is much more than the expected 20%. For 100 mm loss was 86%, for 70 mm - 97%. The loss per 1 meter of 150 mm of the fiber is about 24%.

In order to direct the maximum amount of luminous flux into an acrylic rod-light pipe with a diameter of 30 mm, a conical reflector with an angle of 20° was used. The luminous flux at the output end was 26 lm. Losses accounted for 98%.

The theoretically possible luminous flux can be estimated using the data on the attenuation of white light in PMMA (acrylic) provided by the «Technology Center for Polymeric Optical Fiber» in Tver (Figure 10).

For ease of calculation, we take the power consumption of the LED matrix for the output. It follows that the light output is 90 lm / W.

The length of the acrylic rod is 200 mm, however, the radiation should propagate in the acrylic light pipe at certain angles in order to have minimal losses. The main sources of losses are scattering and absorption of light in the fiber. The light signal can be scattered on material inhomogeneities, on bulk defects, as well as at the boundary with the cladding or at the fiber ends [4,6,9]. The losses associated with these mechanisms depend on the production technology and can be significantly reduced by optimizing it. Contribution to total losses is also made by absorption by impurities and fundamental absorption. Among hydrocarbon POFs, polymethylmethacrylate (PMMA) has the lowest losses. The minimum loss for a given acrylic rod is 250 Db / km for a wavelength of 550 nm, which is quite a lot. The minimum possible loss for POF is approximately 70 Db / km; special additives are used for this, which increases the cost of POF production [2,3,5,8,9].

The luminosity of the light pipe determines the numerical aperture (NA) - the maximum angle of the conical beam of rays that can pass through the light pipe:

\[ NA = \left( n_1^2 - n_2^2 \right)^{1/2}. \]

The numerical aperture of this acrylic light pipe is 0.45. It follows that the maximum angle of radiation input for a given light pipe is equal to \( \arcsin (0.45) \approx 27. \)

That is, if the radiation is introduced into the light pipe at angles from 0 to 27, then it will propagate in the light pipe with full internal reflection with minimal losses.

Considering that radiation is input at the required angles, and its losses are associated only with the quality of the acrylic rod-light pipe, and the input radiation power at the end of the rod is equal to the consumed power of the matrix, as well as the minimum optical path is 2000 mm, we have:

\[ Q_{11} = 16 \cdot 10^{0.1 \left( -\frac{12.23}{1000} \right)} \]
\[ P_{out1} = \sum_{n=1}^{51} Q_{11} = 10.95877W \]
\[ t_{11} = P_{out1} \cdot 90 = 986.29lm \]
\[ Q_{112} = 16 \cdot 10^{0.1 \left( -\frac{dB}{1000} \right)} \]
\[ P_{out12} = \sum_{n=1}^{51} Q_{112} = 11.3612W \]
\[ t_{112} = P_{out12} \cdot 90 = 1022.508lm . \]

The average luminous flux will be 1004.39854 lm.

If we estimate the losses as for a specular light pipe, they are approximately 26% with a light pipe length of 2000 mm. It follows that about 1% of the radiation is “lost” at 1 meter of such rod-light pipe.

The difference between the experimental data and the calculated ones is 38 times, which is explained by the fact that most of the radiation was introduced into the acrylic light pipe at angles greater than the POF angle, i.e. this part of the radiation did not propagate in the light pipe, but was “highlighted” to the sides [3].

Table 4 shows the minimum possible radiation losses under almost equal conditions for transporting radiation over a distance of 2000 mm. The diameter of the specular light pipe is 150 mm and 30 mm, and the diameter of the acrylic light pipe is 30 mm. The results of the calculations are presented under the condition that the semi-aperture of the radiation of the diode matrix using the optical system is converted into the necessary, i.e. for a specular light pipe, it should be minimal, and for an acrylic light pipe, it should not exceed 27. The equality of radiation losses in the optical system of the formation of the aperture in both light pipes is assumed.

### Table 4. Comparison of light pipes

| Light pipe type       | Light pipe length, mm | Semi-aperture, * | Diameter, mm | Radiation loss,% |
|-----------------------|-----------------------|------------------|--------------|-----------------|
| Specular light pipe   | 2000                  | 0.593            | 0.286        | 0.593           |
| Specular light pipe   | 2000                  | 0.796            | 0.067        | 0.796           |
| Acrylic light pipe    | 2000                  | 0.439            | 1.667        | 0.197           |

5. Conclusion

The study of the transmission of light through a specular and acrylic light pipe has shown that under equal conditions of light transport (the same power, the same aperture, the equal length of the light pipe, the same diameter of the light pipe), the acrylic fiber has the advantage. Losses using acrylic light pipe of 2000 mm are 24% whereas using specular light pipe are 45%. However, if there is no limitation in the diameter of the light pipe, then it is preferable to use a specular one. For example, at 150 mm the losses are no more than 13%, which is not achieved with an acrylic light pipe even with a diameter of 10 mm, since when the radiation aperture is kept, a reduction in diameter leads to an increase of the interaction of the radiation with the walls of the acrylic rod and increase of the optical path.

The feasibility of using one of the types of light pipes is determined by the specific task, in which the possible or necessary diameter is installed.

The expediency of the use can be assessed by the example of a 250 W DRL lamp and a light output of 55 lm / W. It follows that the luminous flux of such a lamp is about 14,000 lm.

In order to have the same luminous flux (14,000 lm) at the end of the light pipe 2000mm long, it is necessary to have a diode matrix with a luminous flux of at least 17,000 lm for acrylic light pipe, and at least 15,700 lm for a specular light pipe. Modern LED matrixes allow you to create a luminous flux of 20,000 lm or more. This means that the length of the light pipes can be increased. For example, when
using a 150mm specular light pipe, using a diode matrix with a flow of 20,000 lm allows you getting a luminous flux of 14,000 lm at a distance of about 6 m, and when using an acrylic light pipe with a diameter of 30 mm - 4 m.

The use of “STAL” will allow you to provide illumination of roads \ streets \ squares according to BR 52.13330.2011, i.e. from 6 to 30 lx depending on the class of the object.

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