Light & Engineering
Vol. 28, No. 2, pp. 54–60, 2020
https://doi.org/10.33383/2019-035
Svetotekhnika #6, 2019, pp.31-36

STUDY OF LIGHTING SYSTEMS WITH EXTENDED HOLLOW LIGHT GUIDES

Alexei I. Sterkhov[1], Alexander V. Palagin[1], and Igor Yu. Loshkarev[2]*

[1] Solargy group LLC, Izhevsk
[2] N.I. Vavilov Saratov State Agricultural University, Saratov
** E-mail: igyulo@mail.ru*

ABSTRACT

The article contains comparative results of studying of spectral characteristics of two different light transporting systems: based on *DF2000MA* polymer film (marketed) and based on vacuum-deposited silver coated with silicon and titanium oxides (own development). Studying of *Alanod miro Silver 4270AG*, *Alanod miro Silver 4400AG* and *Alanod miro Silver 4400GP* variants of *Alanod miro Silver* retroreflective material showed that chromaticity of output light of our light guide system is almost the same as that of input natural daylight in visible spectrum. Advantages of optical elements for the light guide system developed by us over those applied in the reference system are demonstrated.

Keywords: light guide, extended hollow light guide, illumination, daylighting, spectrum

1. INTRODUCTION

As known, application of lighting systems based on extended hollow light guides for daylighting of premises is one of the solutions of the problem of reduction of power consumption for lighting. We developed our own lighting system of this type with reflective material based on vacuum-deposited silver, and the goal of this work is to compare it with an existing market analogue with reflective material based on *DF2000MA* polymer film in terms of chromaticity transmission accuracy, integrated transmittance of both the system as a whole and its optical elements as well as technology of manufacturing of reflective tube, system service life, etc.

2. OBJECTS OF RESEARCH

As the subjects of study, the models of a lighting system with a light guide based on *DF2000MA* polymer film and our development *Solarway,* light guide system with the reflective tube based on vacuum-deposited silver coated with silicon and titanium oxides (Fig. 1), have been used.

Elements of the *Solarway* system:

• Light pickup dome: Transparent acrylic sheet with fine texture (*Acryl 92-Z*); made of PMMA *Plexiglass* (by vacuum shaping);

• Thermal barrier: acrylic sheet with thickness of 4mm;

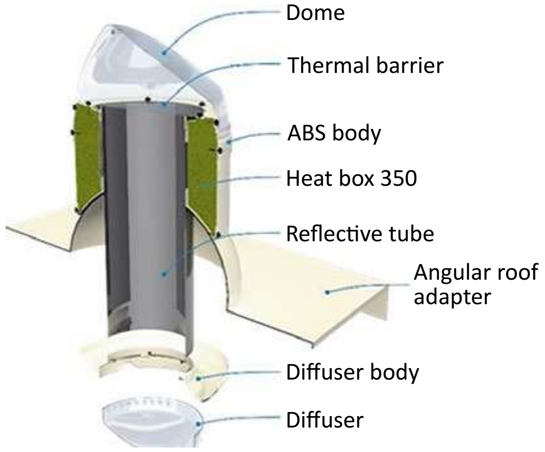

Fig. 1. Scheme of the designed *Solarway* natural lighting system

Fig. 2. Models of the *Solarway* system

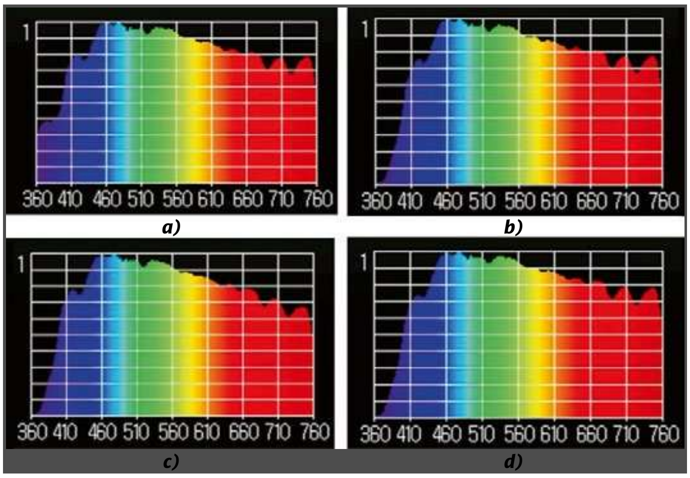

Fig. 3. Relative spectral distribution of radiant energy (as of the moment of measurement): *a*) natural daylight at the moment of measurement, T_{aver} = 5850 K, R_a = 99; *b)* at output of the system with *Alanod miro Silver 4270AG* reflective material; T_{aver} = 5850 K, R_a = 99; *c)* at output of the system with *Alanod miro Silver 4400GP* reflective material, T_{aver} = 5900 K, R_a = 99; *d*) at output of the system with *Alanod miro Silver 4400AG* reflective material, T_{aver} = 5750 K, R_a = 99

- Reflective tube: based on vacuum-deposited silver coated with silicon oxide SiO_2 with low refractive index and titanium oxide TiO_2 with high refractive index;
- Diffuser: transparent acrylic sheet with coarse texture (*Acryl 92-W*) made of PMMA *Plexiglass XT 0A000 Z* (by means of laser cutting).

3. METHOD FOR LIGHT SPECTRAL DISTRIBUTION EVALUATION

The measurements were made:

1. On 01.10.2014, at the latitude of Moscow, at 14:00–14:15 Moscow time, south-easterly, horizon angle of 60°, average illuminance of (5300–5500) lx and cloud cover of about 8 oktas, within the range of λ of (360–760) nm;

2. By means of standard calibrated mobile spectrometer *MK 350* (by *URPtek*, Taiwan); measured parameters: relative spectrum distribution of radiation, correlated colour temperature T_{cp}, and general colour rendering index R_a at input and output of the system; for each object, 5 measurements were made.

The measurements were made for 3 variants of the material of *Solarway* system light guide tube: *Alanod miro Silver 4270AG*; *Alanod miro Silver 4400GP* and *Alanod miro Silver 4400AG*.

The dimensions of the light-guide tube model are as follows: length of 200 mm and diameter of 90 mm (Fig. 2).

Measured values of T_{cp} of natural outdoor lighting varied within the range of

(5750–5900) K and values of T_{cp} at output of the tube of *Alanod miro Silver 4270AG*, *Alanod miro Silver 4400AG* and *Alanod miro Silver 4400GP* were 5850 K, 5750 K and 5900 K respectively.

The study started with measurement of relative spectrum of natural daylight radiation and was continued for three variants of material of the light guide reflective tube at output. The results of this part of the study are presented in Fig. 3 and Table 1.

According to Table 1 and Fig. 4, relative radiation spectrum at output of the light-guide systems is almost equal to that at input.

Fig. 4 demonstrates that, within the λ range of (435–760) nm, relative spectra of radiation of systems with *Alanod miro Silver 4270AG*-based and *Alanod miro Silver 4400AG*-based light guide are equal to relative spectrum of radiation (natural) at input whereas relative spectrum of radiation of the *Alanod miro Silver 4400GP*-based system is slightly lower in the right part of this range.

Table 1. Relative Spectral Distribution of Energy of Daylight Radiation at Input and Output of the Light Guide Systems

Wavelength, nm	Input	Alanod miro Silver 4270AG light guide	Alanod miro Silver 4400GP light guide	Alanod miro Silver 4400AG light guide
385	0.39	0.21	0.23	0.21
390	0.41	0.29	0.31	0.28
400	0.60	0.51	0.56	0.50
410	0.75	0.68	0.72	0.66
420	0.79	0.75	0.77	0.73
430	0.76	0.74	0.75	0.73
440	0.88	0.86	0.86	0.85
450	0.97	0.97	0.96	0.95
460	0.99	0.99	0.99	0.98
470	0.98	0.98	0.98	0.98
480	0.99	0.99	0.99	0.99
490	0.95	0.95	0.95	0.96
500	0.96	0.96	0.96	0.96
510	0.95	0.95	0.95	0.93
520	0.92	0.92	0.92	0.93
530	0.96	0.96	0.96	0.97
540	0.96	0.96	0.95	0.97
550	0.96	0.95	0.94	0.96
560	0.92	0.92	0.91	0.93
570	0.90	0.89	0.89	0.90
580	0.90	0.89	0.89	0.90
590	0.87	0.87	0.86	0.88
600	0.87	0.87	0.86	0.88
610	0.86	0.86	0.85	0.87
620	0.83	0.83	0.82	0.85
630	0.81	0.81	0.80	0.83
640	0.83	0.83	0.81	0.84
650	0.80	0.80	0.78	0.81
660	0.80	0.79	0.77	0.81
670	0.81	0.80	0.78	0.82
680	0.78	0.78	0.75	0.79
690	0.70	0.70	0.67	0.71
700	0.76	0.76	0.71	0.77
710	0.78	0.77	0.71	0.78
720	0.68	0.68	0.62	0.69
730	0.71	0.70	0.63	0.71
740	0.77	0.76	0.67	0.77
750	0.77	0.76	0.66	0.77

Table 2. Spectral Characteristics of Reflective Material of the Light Guide Lighting Systems

Parameters	Technology based on *DF2000MA* polymer film coated by laminating (*Solatube*)	Technology based on *DF2000MA* polymer film coated by laminating (*Solarspot*)	Technology based on vacuum-deposited silver coated with silicon and titanium oxides (*Solarway*)
Integral reflectance of reflective material	99.7 %	99.7 %	Alanod miro Silver 4270AG → 99.8 % Alanod miro Silver 4400AG → 99.8 % Alanod miro Silver 4400GP → 99.8 %

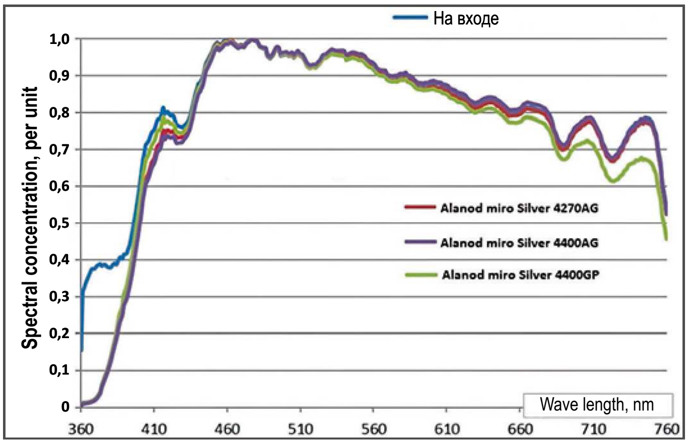

Fig. 4. Graphs of spectra of relative spectral distribution of daylight radiation distributon at input and output of the *Solarway* system with *Alanod miro Silver 4270AG*, *Alanod miro Silver 4400GP* and *Alanod miro Silver 4400AG* variants of light reflecting material

Within the wavelength range (360–410) nm, all these three variants of reflecting material have spectral deviations from the natural daylight radiation due to the fact that acrylic materials contain UV-absorbing photostabilizers protecting acrylic polymer from destructive effect of UV radiation. These spectral differences do not constitute a significant disadvantage since human eye is low sensitive in this range of wavelength. The latter is also proved by the fact that, according to our measurements, all three variants provide maximum possible value of R_a inherent for daylight at output of the system, which is about 99[1].

Integral reflectance of all three variants of reflective material of the *Solarway* system is at the same level as, or higher than, that of microstructure polymer film of the compared light-guide system (Table 2).

Let us consider the differences between manufacturing technologies of these reflecting materials:

Reflective microstructure polymer film is manufactured by depositing dissolved silver and other metals on its base and their further binding by an interferential layer. The film is glued to aluminium base. Application of *DF2000MA* reflective film as a reflective material of light transportation systems [4] is associated with relative risk and special operation conditions: it should not be used as a reflector for sources of radiation without UV-absorbing filter [4]; its operating temperature should be equal to (22–49)°C; when using intensive sources of radiation like light emitting diodes, a protective structure minimising radiant exposure and film heating should be also designed. (Such sources of radiation may cause modification and darkening of its surface.) The basic models showed that first modifications of surface colour begin after reaching the value of radiant exposure of 50 kJ/mm² within the wavelength range (420–500) nm at film temperature of 50 °C.

MiroSilver specular reflective material is produced by depositing vaporized silver on aluminium base and its binding by SiO_2 and TiO_2 oxides. In this case, no glue is used.

Unlike deposited silver, the film material may sometimes be not appropriate due to delamination

[1] If necessary, these differences between natural radiation and output radiation of light guide systems may be slightly reduced by manufacturing the lower diffuser which does not require UV protection of acryl without UV-absorbing additives.

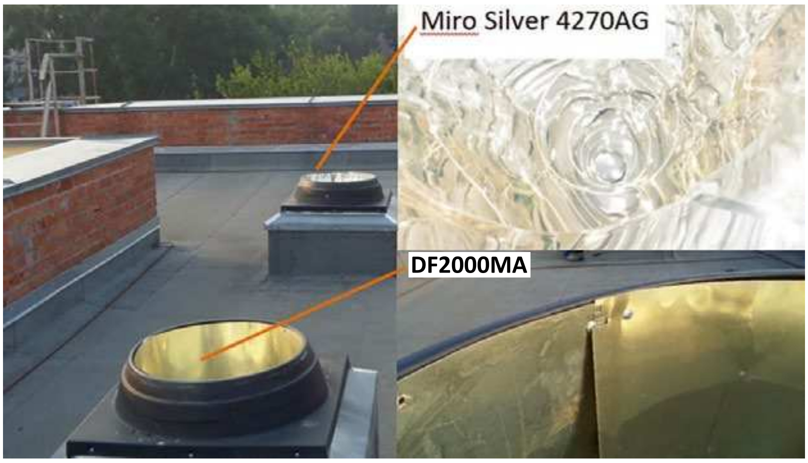

Fig. 5. Appearance of light guides of the two compared systems (2013 variant)

Fig. 6. Appearance of the reflective tube of the light guide based on *DF2000MA* polymer film after a certain period of operation without UV-absorbing filter

of film which lowers characteristics of transmission of natural daylight.

Another one problem of the study was to research the effect of UV radiation on the elements of the *Solarway* system.

In 2016, technical maintenance of the light guides was conducted (4 years after installation). One of them contained *DF2000MA* reflective film material and the other contained the material based on vacuum-deposited silver coated with SiO_2 and TiO_2 oxides (Fig. 5). The domes for both systems were made of PMMA without UV protection. In 4 years, *DF2000MA* reflective material became completely yellow (Fig. 6). However, even yellow material reflects almost the whole spectrum of light with distortions in the yellow, red or green regions of the spectrum but these distortions are not seen but human eye.

PMMA is used for production of light guide domes. This material cuts off most of input UV radiation (at least 72.5 %), however, even a non-significant fraction of this radiation leads to yellowing of reflective material. For additional blocking of this radiation, anti-condensation disc (thermal barrier) also made of PMMA is used in some systems.

Ground UV radiation, mostly within the wavelength range (300–400) nm, getting inside the light guide with *Alanod miro Silver 4400AG*, *Alanod miro Silver 4270AG,* or *Alanod miro Silver 4400GP* reflective materials, does not affect their silver coating adversely since it is almost completely reflected.

Then comparative studies of optical elements of our light guide system *Solarway* (*Solargy SW 250* model, light guide diameter of 250mm) and the light guide system based on *DF2000MA* polymer film (*Solatube 290DS* model, light guide diameter of 350mm) were conducted[2]. The measurements were made by means of *DT-1309* illuminance meter with measurement range of $(1\times10^{-1}–4\times10^{5})$ lx on February 27, 2017 under overcast sky with cloud cover of (8–10) oktas.

Efficiency of the light guide system may be justified based on integrated transmittance τ_o calculated using daylight factor calculation methodology for sidelight systems with different building arrangement schemes in urban development conditions as well as for premises with overhead (by means of lanterns with different designs) and combined (overhead and side) natural lighting systems [11]:

$$\tau_o = \tau_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \tau_5,$$

[2] Length and diameter of light guides make no difference as measurements were made without a reflective tube.

Table 3. Comparative, Declared by the Manufacturer, Characteristics of Optical Elements of Light Guide Lighting Systems Without Reflective Tubes

Characteristics	Technology based on *DF2000MA* polymer film (*Solatube 290 DS*)	Technology based on vacuum-deposited silver coated with silicon and titanium oxides (*Solargy SW 250*)
Light collector and dome manufacturing technology Transmittance τ_1	PC or PMMA, *Plexiglass* casting method (Germany) 0.83 [6] or 0.92	PMMA, vacuum moulding method, *Plexiglass* (Germany) 0.92
Diffuser Transmittance τ_4	*Dual Diffuseur Optiview®* *Dual Diffuseur Vusion®* 0.82 or 0.79	PMMA, *Plexiglass XT 0A000Z* laser cutting (Germany), 0.90
Integrated transmittance τ_0 (τ_2 = 0.9, τ_4 = 0.9, τ_5 = 1.0, taken equal for both systems)	0.55 or 0.58	0.67
Factors	High shock resistance UV radiation integral transmittance of 72.5 %	High shock resistance UV radiation integral transmittance of 72.5 %

Table 4. Comparison of Output Illuminance (lx) of Light Guide Elements (Without Reflective Tube) of *Solargy SW* and *Solatube 290 DS* Systems

System element name	Solatube 290 DS			Solargy SW 250		
	Without element	With element	Element(s) integral transmission	Without element	With element	Element(s) integral transmission
Dome	23,750	15,675	0.66	24,235	23,265	0.96
Thermal barrier	no	no	–	23,563	21,910	0.93
Diffuser	24,255	20,130	0.82	23,900	21,271	0.89
All elements simultaneously and sequentially arranged above each other	21,455	11,753	0.55	21,205	16,498	0.77

where τ_1 is the transmittance of material (system) defined using [11, Table B.7]; τ_2 is the coefficient of light losses at light opening sashes also defined using [11, Table B.7] (light opening dimensions are taken equal to dimensions of sash box based on external measurement); τ_3 is the coefficient of light losses on load bearing structures defined using [11, Table 8] (τ_3 =1 for side lighting); τ_4 is the coefficient of light losses at sunlight-protecting devices defined in accordance with [11, Table B.8]; τ_5 is the coefficient of light losses in protecting net installed above lanterns taken equal to 0.9 [11].

Table 3 demonstrates that the declared values of τ_o without consideration of reflective tube for the compared models *Solargy SW 250* and *Solatube 290 DS* equal to 67 % and 58 % respectively.

It follows from Table 4 that total optical losses amount to 45 % in elements of *Solatube 290 DS* and 23 % in elements of *Solargy SW*. Therefore, in *Solatube 290 DS* major optical losses are associated with its optical elements. This allows a definitive conclusion to draw: the level of light transmission of the elements of the developed system is 1.4 times higher than that of the compared *Solatube* system.

4. CONCLUSION

Comparative study of light guide lighting systems based on *DF2000MA* polymer film and on vacuum-deposited silver coated with silicon and titanium oxides are conducted. Spectral measurements demonstrated slight advantage of the developed *Solarway* system in terms of integral reflective ability of reflective tube reflective material. The *Solarway* system was studied for three variants of *Alanod miro Silver* reflective material. Chromaticity of *Solarway* output light within the λ range of (410–760) nm is absolutely identical to input natural daylight for two of them, *Alanod miro Silver 4270AG* and *Alanod miro Silver 4400AG* and is close to natural daylight for the third one, *Alanod miro Silver 4400GP*, being slightly less in the far-red region of wavelength (660–760) nm. In the violet range of λ (385–410) nm, all variants of *Alanod miro Silver* cause non-significant optical losses.

In general, according to measurements, the reflective tube with *Alanod miro Silver* transmits natural daylight (within the range of λ (385–750) nm) almost completely and without spectral distortions.

The reflective material of the designed *Solarway* system demonstrated its advantage in terms of service life (without UV radiation protection) over *DF2000MA* film material: 25 years and 10 years respectively. Moreover, unlike multi-polymer film, it is reliable (does not delaminate) in northern climatic areas of the Russian Federation.

Comparison of some light-engineering characteristics of optical elements of the designed system (*Solarway*) and the marketed one (*Solatube*) demonstrated significant advantage of the former.

REFERENCES

1. URL: http://www.solarway.su/ (date of reference: 26.04.2019).

2. Palagin, A.V., Sterkhov, A.I., Korepanov, E.V.. Comparison of Functional and Energy Factors of Natural Daylight Lighting Systems of Buildings [Sravneniye sistem estestvennogo osvachsheniya zdaniy po funktsionalno-energeticheskim faktoram] // Intellektualniye sistemy v proizvodstve, 2014, Vol. 2 (24), pp. 191–194.

3. Solovyov, A.K. Hollow Tube Light Guides and their Application for Natural Lighting of Buildings [Polyiye trubchatyie svetovody i ikh primeneniye dlya estestvennogo osveshcheniya zdaniy] // Promyshlennoye i grazhdanskoye stroitelstvo, 2007, Vol. 2, pp. 53–55.

4. URL: https://multimedia.3m.com/mws/media/982449O/3mtm–specular–film–df2000ma–technical–data–sheet.pdf (date of reference: 26.04.2019).

5. URL: http://www.napcso.hu/my_content/dok/CSTB_Report_2011.pdf (дата обращения: 26.04.2019).

6. URL: http://www.cstb.fr/pdf/atec/GS06–G/AG142204.pdf (date of reference: 26.04.2019).

7. URL: http://www.bibliorossica.com/book.html?currBookId=10063 (date of reference: 26.04.2019).

8. URL: https://solarspot.co.uk/wp–content/uploads/2018/01/BRE–Testing–of–light–tubes.pdf (date of reference: 26.04.2019).

9. URL: http://www.casaportale.com/public/uploads/relazione_ebner.pdf (date of reference: 26.04.2019).

10. URL: http://www.geinnovations.net/solarspot-news_court.html (date of reference: 26.04.2019).

11. SP 23–102–2003 "Design and Construction Regulations. Natural Lighting of Residential and Public Buildings".

Alexei I. Sterkhov, engineer. Graduated from Izhevsk GTU in 2009. Technical director of Solargy group LLC. Research interests: lighting, energy saving, light guides

Alexander V. Palagin, engineer. Graduated from Izhevsk GTU in 2009. Chief Researcher of Solargy group LLC. Research interests: lighting, energy saving, light guides

Igor Yu. Loshkarev, Ph.D. in Technical Sciences. In 1993, graduated from Saratov M.I. Kalinin Agriculture Mechanisation Institute (winner of the Mark of Honour award). Associate professor of the Engineering Physics, Electric Equipment and Technologies sub-department of N.I. Vavilov Saratov State Agricultural University. Research interests: lighting, energy saving, light guides