Restoration of Optical Spectrum

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Abstract. *This article deals with research of luminous sources which could be applied in indoor Free Space Optic (FSO) networks. Indoor FSO networks have potential to replace standard IEEE 802.11 in the future. Suitable selection and configuration of optical radiation sources can at the same time provide communication and lighting in indoor spaces. This article is engaged in spectral mergence of optical sources, willful suppression of part of emitted visible spectrum and consequential restoration of this optical spectrum.*

Keywords

Correlated Color Temperature, indoor FSO, laser diode, LED diode, optical spectrum, restoration.

1. Introduction

The users of data networks have two main requirements, high data rate and mobility. In indoor spaces the standard IEEE 802.11, known as Wi-Fi, fulfills these requirements. However, this standard gets near to its limits of transmission and capacity possibilities, therefore it is necessary to develop other technologies. The solution could be networks using optical waves.

2. Indoor FSO Networks

The FSO networks use radiation of light to data transmission, the transmission medium is the air. The indoor FSO networks work inside buildings. Their advantage comparing to the outdoor FSO networks is that they are not so much influenced by the atmospheric effects. The range of the indoor FSO networks covers the given room only, the optical waves cannot penetrate the adjoining rooms and that is why these networks are more resistant to eavesdropping. The other advantages are low cost of the components for optical communication, their small size and low power consumption, which are important parameters.

The disadvantage of the indoor FSO networks is link extinguishment by people or by some objects. Another problem is optical noise. This optical noise can be caused by either room lighting, light bulbs, or by fluorescent lamps. The sunlight causes optical noise too. These unwanted light sources are called ambient light.

The indoor FSO networks are divided according to the line of sight between a transmitter and a receiver and according to the direction. The first criterion classifies them into the networks with a line of sight and into the networks with a non-line of sight. According to the direction there are directed, non-directed and hybrid networks [1]. All these possibilities are in Fig. 1, where TX is a transmitter and RX is a receiver.

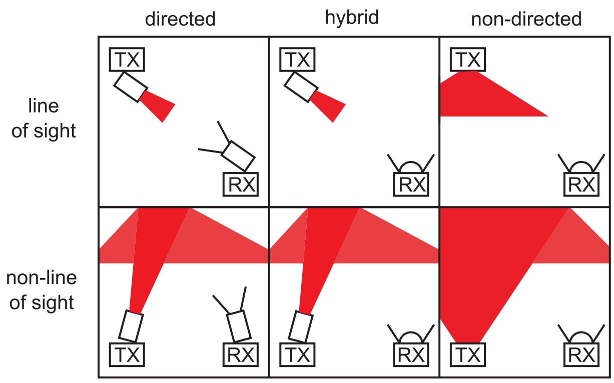

Fig. 1: Classification of indoor FSO networks.

The indoor FSO networks can also be divided in accordance with the type of the optical spectrum that they use for their activity. There are networks using infrared radiation. These networks are built on the experiences with infrared radiation used in remote controls of home electronics. The most used wavelengths are 850 nm, 950 nm, 1300 nm, 1480 nm and 1550 nm [2].

The indoor FSO networks also use a visible light for communication, most often white LED diodes. The data are transmitted by modulation of LED diodes, the On-Off Keying modulation is used [3]. The LED diodes emitting white light include a blue light emitting chip and yellow luminophore from YAG (Yttrium, Aluminum, and Garnet) [4]. The white light originates by a chemical reaction between the blue light and the luminophore. This chemical reaction cannot be faster and that is why the modulation of white LED diodes has its impassable limits. The LED diodes emitting white light are also made out of three luminous sources, which emit the basic colors, blue, green and red. If the white LED diodes are to be used for communication in the indoor FSO, then the power LED diodes are needed. The white power LED diodes are supplied by forward current of up to 700 mA [5]. The construction of such a circuit closer that would be able to switch on and off such a high level of forward current very quickly, is difficult. Therefore these LED diodes have limits of modulation as well.

For the indoor FSO networks ultraviolet radiation is also used. The advantage is that the ultraviolet light is not so dangerous for the human eye, and hence higher power can be used. Light bulbs, fluorescent lamps and the Sun do not almost emit in a nearby ultraviolet region and that is why these sources do not cause so much noise in communication [6].

The objective of the research team is to construct such an optical transmitter that would provide lighting and communication at the same time. A white power LED diode will be used as an illuminative source, but it has its own modulation limits. Therefore some part of the emitted spectrum will be suppressed by a narrow optical filter and the suppressed part will be replaced by a suitable LED diode or a laser diode. The aim is to restore the original spectrum of a white power LED diode as accurately as possible. The communication data will be transmitted by a communication LED diode, whereby the limitation of a white LED diode will be avoided. The aim is to use visible light only for the transmitter to provide both illumination and communication at the same time. Using of other luminous sources, e.g. the sources from the infrared optical spectrum, would not meet the requirements necessary for visible light. Using of other visible luminous sources emitting in an area in which white power LED diodes emit a relatively small amount of light (470 nm), might cause shifting of the originally emitted spectrum, the white light would not then be originally white, which the human eye can recognize.

3. White Power LED Diode

For illumination the white power LED diode Luxeon 5W Star by the Philips Company was chosen. The marking of this LED diode is LXHL-LW6C. All important parameters are given in the datasheet [5]. This power LED diode is optimally supplied by the current of 700 mA. The luminous flux is 120 lm, the color temperature is 5500 K and the viewing angle is 120 °.

The spectral characteristic of this power LED diode was measured in a laboratory by spectrometer USB650 by the Ocean Optics Company. The ambient noise was taken off from the measured data. The spectral characteristic of the white power LED diode supplied by the forward current of $I_f = 700$ mA is in Fig. 2.

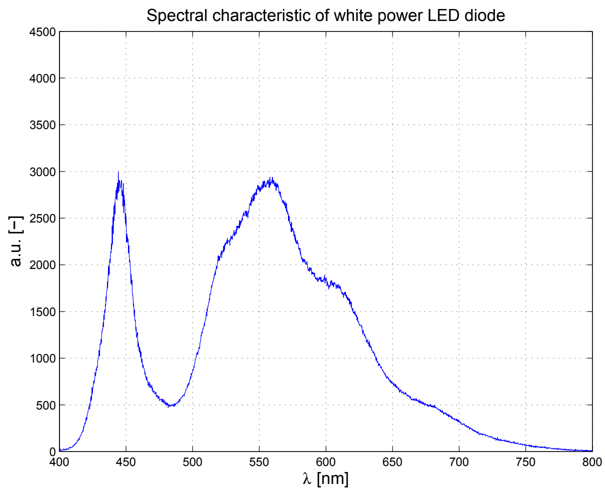

Fig. 2: Spectral characteristic of white power LED diode.

The optical filter is used for suppression of spectral part emitted by a white power LED diode. The filter that was chosen was the notch filter [7], the supplier was Edmund Optics. The features of this notch filter, which the supplier provides, are in Tab. 1.

Tab. 1: The features of notch filter.

Feature	Value
Diameter	25 mm
Central Wavelength λ_c	532 nm
Full Width at Half Maximum (FWHM)	$26,6$ nm
FWHM Tolerance	$\pm 2,7$ nm
Transmission Wavelength	$400 - 700$ nm
Transmission	90 %
Reflection at Central Wavelength	99 %
Optical Density	4

The spectral transmission of this notch filter was measured in a laboratory. The application to the spectrometer measures and stores the original spectrum uninfluenced by the notch filter in its memory. Afterwards, it measures and stores the dark spectrum. Now, the application measures the spectrum with a notch filter inserted between the light source and the spectrometer and it calculates the spectral transmission according to the following Eq. (1):

$$T_\lambda = \frac{S_\lambda - D_\lambda}{R_\lambda - D_\lambda}, \tag{1}$$

where S_λ is sample intensity at a wavelength λ, R_λ is reference intensity at a wavelength λ and D_λ is dark intensity at a wavelength λ. Spectrometer USB650 was used again. The diagram of spectral transmission measurement is in Fig. 3. The spectral transmission of the notch filter is in Fig. 4.

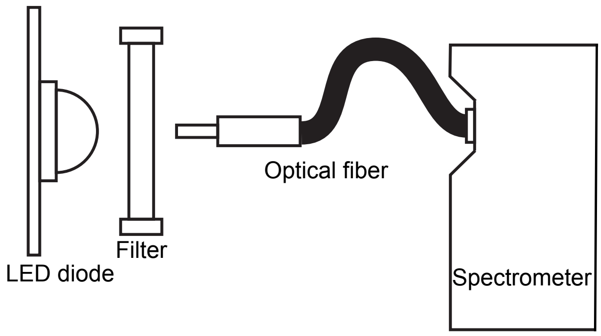

Fig. 3: Diagram of spectral transmission measurement of the notch filter.

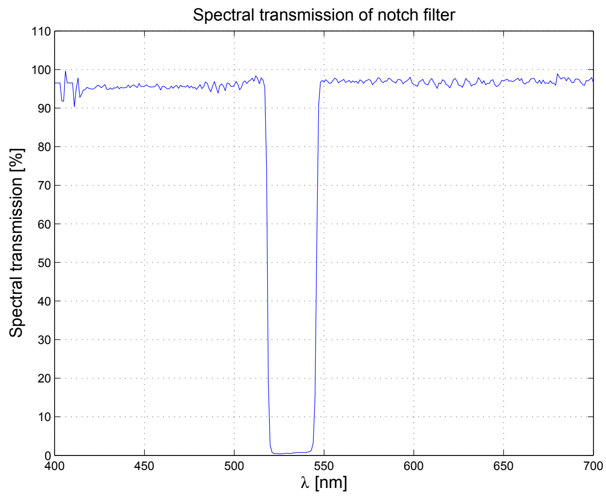

Fig. 4: Spectral transmission of notch filter.

It was read from the spectral transmission in Fig. 4 that the central wavelength was 532,5 nm. FWHM was 27,5 nm. The measured data correspond to the data written in the datasheet.

Inserting the optical filter between a white power LED diode and a spectrometer causes suppression of the original spectrum, which is shown in Fig. 5.

4. Optical Spectrum Restoration of White Power LED Diode

For the optical spectrum restoration of the white power LED diode a LED diode and a laser diode with suitable

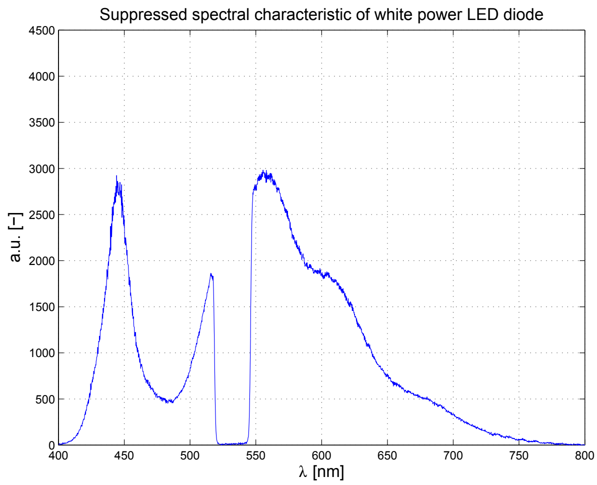

Fig. 5: Suppression of spectral characteristic of a white power LED diode.

wavelengths were chosen to compensate the suppressed spectrum.

4.1. LED Diode LED535-01

The features of this LED diode given by the manufacturer are in Tab. 2 [8].

Tab. 2: Features of LED diode LED535-01.

Feature	Value
Central Wavelength λ_c	535 nm
FWHM	35 nm
Optical Power	4 mW
Typical Forward Voltage	$3,2$ V

Figure 6 shows the measured spectral characteristic of LED diode LED535-01. According to the measured values the central wavelength is at 533,0 nm and FWHM is 43,7 nm.

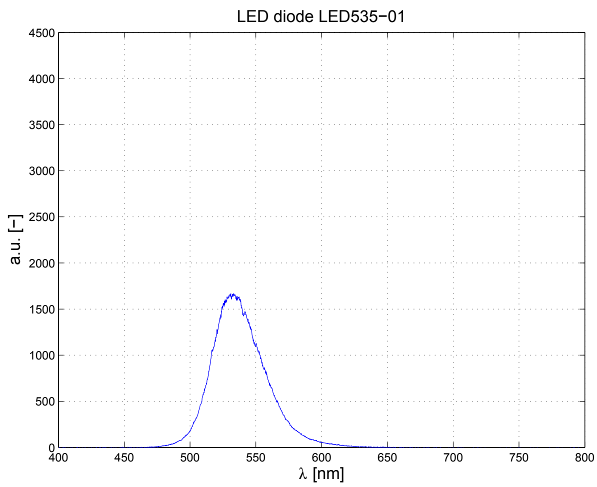

Fig. 6: Spectral characteristic of LED diode LED535-01.

4.2. Laser Diode L10H532

The features of this laser diode given by the manufacturer are in Tab. 3 [9].

Tab. 3: Features of LED diode LED535-01.

Feature	**Value**
Central Wavelength λ_c	532 nm
FWHM	1, 5 nm
Optical Power	10 mW
Typical Forward Voltage	3, 0 V

Figure 7 shows the measured spectrum emitted by the laser diode. According to the measured values the central wavelength is at 532,2 nm and FWHM is 1,8 nm.

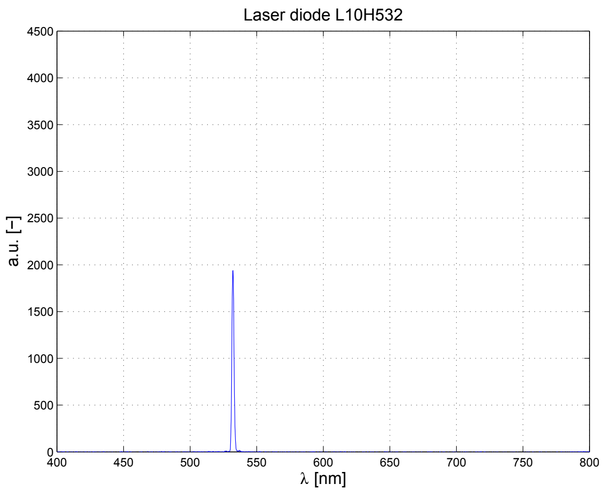

Fig. 7: Spectral characteristic of laser diode L10H532.

5. Merging of Spectra

Merging of the spectra was measured in a laboratory by spectrometer USB650. The evaluative criterion of the optical spectrum restoration was the Correlated Color Temperature (CCT). The CCT of the white power LED diode was measured first and then the CCT after the restoration. Both values were compared with each other. The spectrum of the white power LED diode is a reference since the aim is to approach the original spectrum as much as possible so that the human eye cannot recognize the suppression and the restoration of the spectrum.

The correlated color temperature CCT of a white light source is defined as the temperature of a planckian black body radiator, the color of which is closest to the color of a white light source. The correlated color temperature is used if the color of a white light source does not fall on the planckian locus [10].

5.1. Restoration by LED Diode LED535-01

The Correlated Color Temperature CCT was measured three times in all and the measured values are written in Tab. 4. Merging of the spectra is in Fig. 8.

Tab. 4: Restoration by LED diode LED535-01.

LXHL-LW6C	**Restoration**	**Deviation**
CCT_{org} [K]	CCT_{res} [K]	δ [%]
5127	5205	1, 52
5190	5159	−0, 60
5150	4861	−5, 61

Deviation δ was calculated according the Eq. (2)

$$\delta\ [\%] = \frac{CCT_{res} - CCT_{org}}{CCT_{org}} \cdot 100, \qquad (2)$$

where CCT_{org} is CCT value of original spectrum and CCT_{res} is CCT value of restoration of spectrum.

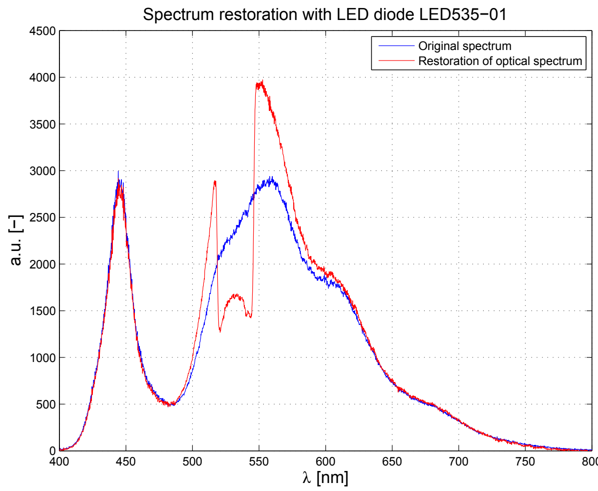

Fig. 8: Restoration by LED diode LED535-01.

5.2. Restoration by Laser Diode L10H532

The CCT was repeatedly measured three times and the measured values are in Tab. 5. Merging of the spectra is displayed in Fig. 9.

Tab. 5: Restoration by LED diode LED535-01.

LXHL-LW6C	**Restoration**	**Deviation**
CCT_{org} [K]	CCT_{res} [K]	δ [%]
5035	4119	−18, 19
5103	4265	−16, 42
5149	4415	−14, 26

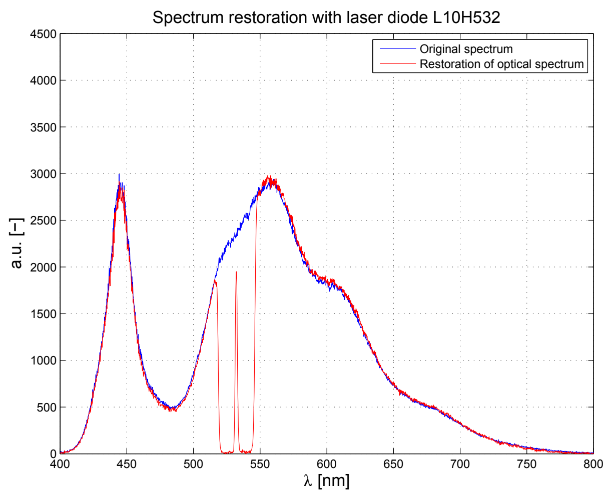

Fig. 9: Restoration by laser diode L10H532.

6. Simulation in LightTools

The restoration was simulated in software LightTools. This software enables modeling of optical systems [11]. Its unique design and analyzing features combined with its simple way of operation, its support of a quick design and optimization make obtaining the results according to the predefined conditions possible. This software includes a component library, in which there are light sources, optical elements, lenses, etc. It is possible to change the selected parameters, optical properties, to import spectral characteristics, etc. In this software the simulation of merging of the spectra was carried out.

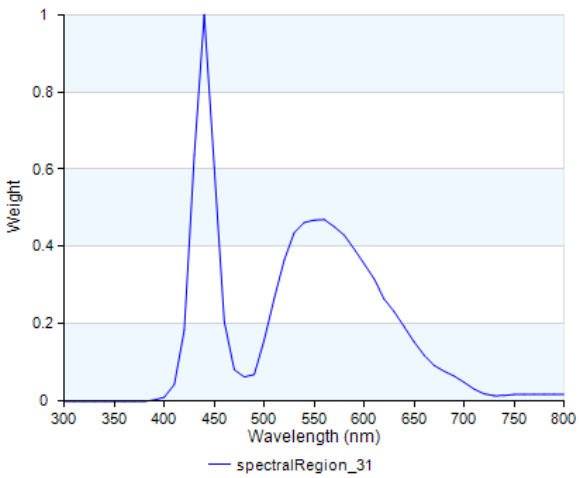

Fig. 10: Original spectrum of power LED diode inserted from library.

The component library of LightTools includes a plenty of LED diodes. From this library a power LED diode was chosen. It has the same parameters as white power LED diode LXHL-LW6C. Unfortunately, the spectral characteristic of this power LED diode does not answer the spectral characteristic of real LED diode LXHL-LW6C. However, the software enables to import the spectral characteristic that had been done before. Figure 10 shows the original spectral characteristic of a white power LED diode from the component library, Fig. 11 shows the spectral characteristic imported from the real measurement.

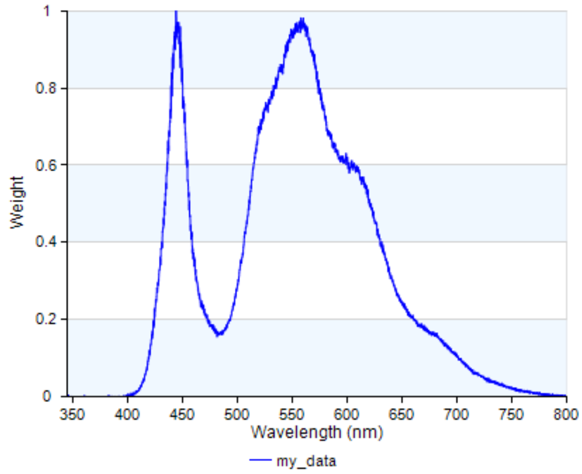

Fig. 11: Modified spectrum of power LED diode according real measurement.

The optical filter was applied on the white power LED diode in the same way as in the real measurement. The suppressed spectrum that was simulated in software LightTools is in Fig. 12.

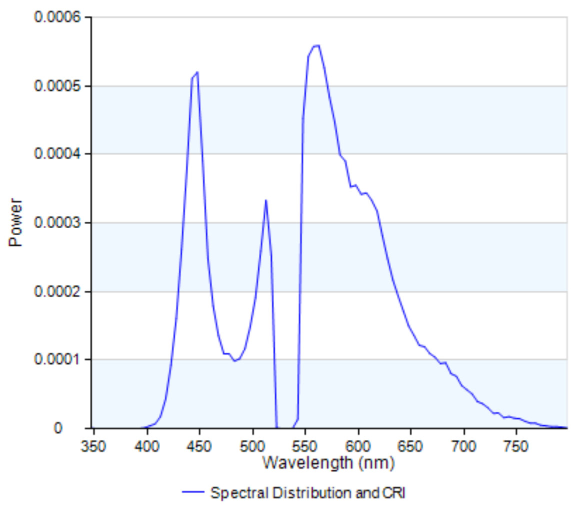

Fig. 12: Suppression of spectral characteristic of the white power LED diode in LightTools.

6.1. Restoration by LED Diode LED535-01 in LightTools

The evaluative criterion was again the correlated color temperature CCT. Software LightTools makes the measurement of this parameter possible. The simulated values of the CCT before the suppression and after the restoration are written in Tab. 6. Figure 13 shows the restoration simulated in the software.

Tab. 6: Restoration by LED diode LED535-01 in LightTools.

LXHL-LW6C	Restoration	Deviation
CCT_{org} [K]	CCT_{res} [K]	δ [%]
5115, 6	4939, 9	−3, 43

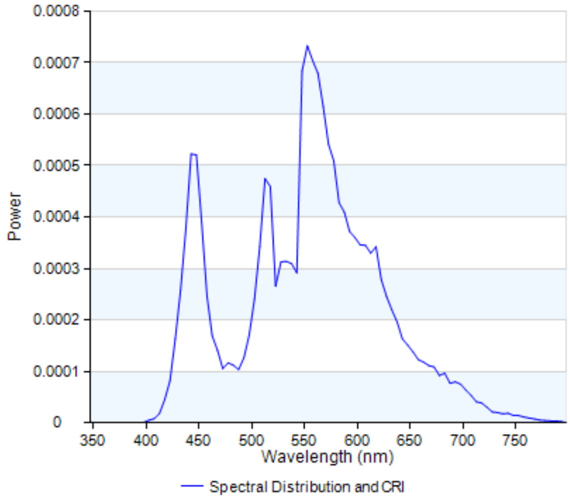

Fig. 13: Restoration by LED diode LED535-01 in LightTools.

6.2. Restoration by Laser Diode L10H532 in LightTools

The values of the CCT simulated in LightTools are in Tab. 7. The restoration by means of laser diode L10H532 is shown in Fig. 14.

Tab. 7: Restoration by laser diode L10H532 in LightTools.

LXHL-LW6C	Restoration	Deviation
CCT_{org} [K]	CCT_{res} [K]	δ [%]
5115, 6	4230, 1	17, 31

7. Conclusion

This article describes the suppression of part of the spectrum emitted by a white power LED diode and the restoration of the suppressed spectrum. Part of

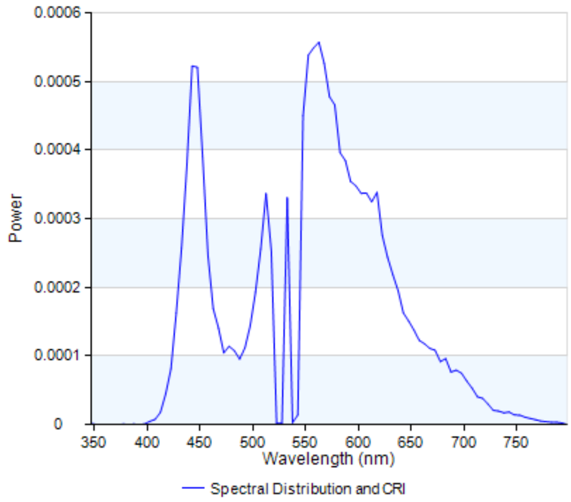

Fig. 14: Restoration by laser diode L10H532 in LightTools.

the spectrum was suppressed by a notch filter. In the first case the restoration of the original spectrum was carried out by means of a LED diode, in the other case by a laser diode. The optical filter showed the features identical with the parameters in the datasheet.

The restoration of the original spectrum by means of a LED diode was very successful. The Correlated Color Temperature CCT served for comparing the results. At first, the CCT_{org} of the white power LED diode was measured; afterwards the CCT_{res} measurement of the spectra merging was carried out. These two values were then compared. In the first two measurements the restoration was very successful; the differences in the CCT values were very small, they were up to 2 %. In the third measurement a higher deviation occurred, it was less than 6 %.

The restoration of the original spectrum by means of the laser diode was not that successful as the restoration by means of the LED diode, which is obvious from the measured values of the CCT. The smallest deviation was greater than 14 %.

The restoration of the original spectrum was also simulated in software LightTools. Because of the simulation the spectral characteristics of both the power LED diode and the laser diode had to be changed according to the real measurements in the laboratory. The results obtained from the simulation are very similar to those measured in the laboratory.

It is therefore suitable to deal with the spectrum restoration by means of the LED diode. The laser diode is inapplicable for this case. It is possible to change the forward current of the LED diode. Due to this, the central wavelength could be slightly shifted and in this way the Correlated Color Temperature after the restoration could be improved. The aim of this research is to maximally approach the CCT value of the white power LED diode. Further intention of the research team is to test other LED diodes, which could replace the original spectrum. The same measurements will be repeated with the new LED diodes.

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Petr SISKA was born in 1979 in Kromeriz. In 2005 he completed his M.Sc. studies at VSB-Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Electronics and Telecommunications. Three years later he completed his Ph.D. studies in the field of Telecommunications Technologies. He is currently employed at the Department of Telecommunications. He is interested in optical communications, fiber optic sensors and Distributed Temperature Sensing systems.

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Vladimir VASINEK was born in Ostrava. In 1980 he graduated in Physics, specialization in Optoelectronics, from the Science Faculty of Palacky University. He was awarded the title of RNDr. at the Science Faculty of Palacky University in the field of Applied Electronics. The scientific degree of Ph.D. was conferred upon him in the branch of Quantum Electronics and Optics in 1989. He became an associate professor in 1994 in the branch of Applied Physics. He has been a professor of Electronics and Communication Science since 2007. He pursues this branch at the Department of Telecommunications at VSB–Technical University of Ostrava. His research work is dedicated to optical communications, optical fibers, optoelectronics, optical measurements, optical networks projecting, fiber optic sensors, MW access networks. He is a member of many societies - OSA, SPIE, EOS, Czech Photonics Society; he is a chairman of the Ph.D. board at the VSB–Technical University of Ostrava. He is also a member of habilitation boards and the boards appointing to professorship.