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Visible light communications with compound spectra

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ABSTRACT

At present the Visible Light Communications (VLC) attract attention of academia and industry thanks to rapid progress in the development of white light emitting diodes (LED). This article deals with the VLC and proposes their new solution, which may help remove some lacks of the current VLC. The substance of the new VLC solution is purposeful suppression of a part of the spectrum by a notch filter and by subsequent reconstruction of the original spectrum. Thus, only a part of the visible spectrum will transmit the information data. This is the main difference in comparison with the current VLC. This might be the way how the crucial parameters of the VLC may be improved.

1. Introduction

Currently, the outdoor and indoor wireless communications are rapidly developing, both radiofrequency (RF) and optical. The Standard IEEE 802.11 known as WiFi has its new version 802.11ac [1], which was presented at the beginning of the year 2014. The Free Space Optic (FSO) links are also quickly developing including the Visible Light Communications as their part. The indoor FSO has several advantages in comparison with RFs [2]. It is expected that in the future some RFs may be replaced by the FSO links. The main advantages of the VLC are non-licensed bandwidths, no interferences, good data security, low power consumption, communication, and illumination [3]. The disadvantage is the appearance of some people or some obstacles in the line-of-sight between the transmitter and the receiver.

The VLC are based on white light emitting diodes (LED). The VLC offer many possibilities of utilization, for example high-speed data communication via lighting infrastructures in offices and in houses, high-speed data communication in trains and buses, high-speed data communication in aeroplane cabins, traffic lights management and communications, car-to-car (C2C) communication, etc. [3,4].

This article consists of several sections. The first section deals with the current VLC. The following sections describe the methods of white light creation in LEDs since white LEDs are the key element of the VLC. On the basis of the white LED limitations, the new type of VLC is also proposed and described. The article is concluded by the functionality verification of spectra compounding in a laboratory and in simulation software. Spectra compounding is the basis of proposed VLC.

2. Current visible light communications

Thanks to visible light transmission, the VLC can provide two important functions at the same time, that is illumination and data communication. Both these functions are realized thanks to the development of LEDs done in the last decades. The classical illumination sources (incandescent light bulbs and fluorescent lamps) are unsuitable for high speed data communications. Their switching persistence is too long and they cannot switch on and off fast enough. In the 1990s, the first high-brightness LEDs appeared for the purpose of illumination and since then they have been considerably developed and their features have been markedly improved.

In comparison with the classical incandescent and fluorescent light sources for illumination, LEDs reach much higher efficiency and their further improvements are expected in the future. The other advantages of LEDs are their longer lifetime, higher tolerance to humidity, a smaller and compact size, minimum heat generation compared with the classical illumination sources, and lower power consumption. LEDs are more ecological because they are mercury free [3].

These advantages are promising. The above described features of LEDs are a good reason for replacing the current illumination sources (both indoor and outdoor). This process has already started. Another feature of LEDs is their fast switching on and off. This

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encourages the data transfer [5].

The first concept, which can be called as VLC, was presented by Pang et al. in 1999 [6]. This concept did not use a white light for communication but it used a visible light therefore it belongs to the VLC in general. The first concept using a white light was proposed by Tanaka et al. at Keio University, Japan, in 2000 [7]. This started the development of these communications. In 2003, the Visible Light Communications Consortium (VLCC) was established in Japan. It associates the Japanese companies dealing with the VLC. In 2007, the VLCC proposed two VLC standards. In the following years, several successful experiments were done with the aim of increasing the data rate and the distance. In 2011, the IEEE published new IEEE Standard 802.15.7 defining physical and access layers for the VLC [8].

3. White light creation

To provide LED illumination, LEDs have to be able to emit white light. There are two main methods of creating white light: color mixing and wavelength conversion [9–11].

Color mixing is based on combining three (or more) color light sources. To create white light by mixing requires correct proportioning of blue, green and red colors. This method can create any color of light. The disadvantage of this method is its higher complexity as well as higher costs. In addition, the illumination requirement of a typical office environment has to be 200–1000 lx [3,12]. That is why the power LEDs are needed because of their sufficient luminous flux. The disadvantage of the power LEDs is their forward current of up to 700 mA [13,14]. It is difficult to switch on and off such a high level of the forward current very quickly.

The wavelength conversion creates phosphorescent white light. The basis is a blue emitting LED coated with a phosphor layer. The yellow phosphor layer is usually YAG (Yttrium Aluminium Garnet) $Y_3Al_5O_{12}$ [9,11]. This phosphor layer absorbs a portion of emission emitted by a blue LED, then phosphorescence occurs and the phosphor layer emits yellow light. This is the wavelength conversion. Yellow emission mixes additively with the nonabsorbed blue component and this way it creates the required white color. This method is easier and cheaper, but the slow response of phosphor considerably limits the modulation bandwidth to a few MHz [3]. This is a great disadvantage. There are several techniques for achieving a high data rate:

- using of a blue filter in a receiver cutting out the slow response of the yellow components [15,16],
- pre-equalization at the LED driving module [17],
- postequalization at the receiver [18,19],
- combination of all the three above-mentioned techniques [20],
- using of more complex modulation schemes and techniques. This approach involves combining of multilevel modulation techniques like the Quadrature Amplitude Modulation (QAM) with the optical Orthogonal Frequency Division Multiplexing (OFDM), or the Discrete Multitone (DMT) [21–24].

This article suggests another technique for possible increasing the data rate. This technique is usable for both types of white LEDs. This technique is based on the principle of using a part of the visible spectrum for the data transmission only. This contrasts to the current VLC based on modulation of the whole emitted spectrum.

4. New approach to visible light communications

The principle of this technique is based on purposeful suppression of a spectrum part emitted by a white LED and on subsequent reconstruction by means of another LED.

The white LED emits almost the whole visible spectrum. A part of this spectrum is purposefully suppressed by an optical filter. The suppressed part of the original spectrum is subsequently replaced by a light from another LED. Let us call this LED the *communication LED*. The suppressed and replaced spectra create the original white light together [25]. The emitted spectrum is not identical with the original but the color temperature is almost the same which is more important for human perception.

In the current VLC, the whole emitted spectrum is used for data communication (is modulated), the white LED is switched on and off. We have described in Section 3, the disadvantages of the white LEDs are that either the white LEDs are supplied by a high level of the forward current (switching problems) or they use the phosphor layer (with yellow component response) for creating the white light. Both these possibilities very complicate the modulation of the white LEDs. Our approach does not modulate the white LED (supplied by the constant forward current) but only the communication LED therefore a yellow component response does not appear, the white LED emits continually. The communication LED is narrow spectral, it does not contain any phosphor layer and it is supplied by lower forward current. The yellow component response takes around 67 ns (and more) which limits the date rate to 15 Mbit s^{-1} [26,27]. In comparison, LEDs made of materials with direct-gap (GaAlAs, GaAlInP, AlGaInN, InGaN, etc.) can provide a maximum data rate of 622 Mbit s^{-1} [11,9]. The spontaneous lifetime of carriers in LEDs in direct-gap semiconductors is of the order of 10^{-8}–10^{-9} s. The communication LED is an InGaN green LED. If we compare the data rates of white LEDs with phosphor layer and direct-gap LEDs then it is obvious that the direct-gap LEDs (the communication LED) are faster in principle. These features may increase the data rate of VLC.

For suppression of the spectrum part, an optical narrow band stop filter called a notch filter is necessary. These filters are commonly commercially available. For an appropriate notch filter, an acceptable LED has to be found to replace the suppressed part, preferably without any modification of its spectrum by the help of some other optical filters. These LEDs are also commercially available. The research objective was to find such forward current of the communication LED that would be able to reconstruct the original white light.

The question is whether it is advantageous to suppress a part of the white source spectrum and then subsequently replace the suppressed part by another light source and to attain correct spatial and spectral merging of the two light beams. Would not a combination of white light for illumination and infra-red (IR) light for communication be better? The answer is not. IR has similar power effect on the human eye to visible light. The human eye is built for visible light and the eyes are able to receive its great amount. Thanks to this the transmitted power of IR has to be limited for human eye protection. While VLC can transmit higher optical powers and generally achieve a higher data rate (>100 Mb s^{-1}) [28,29], IR can provide thanks to power limits only 16 Mb s^{-1} (defined by IrDA [30]). The main advantage of VLC is connection of two functions (illuminations and communications) together and VLC is faster. Therefore VLC is preferable.

5. Measurements in laboratory

White power LED Luxeon 5W Star marked LXHL-LW6C [13] was chosen for illumination. The forward current of this LED is 700 mA, its luminous flux ϕ is 120 lm and the color temperature is 5500 K. The emitted spectrum of this LED is shown in Fig. 1. This spectrum was measured by spectrometer USB650. Let us call this