White Light Transmitting Antenna for Four-spectrum Mobile WDM-VLC

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Abstract. In this paper, we propose a mixing white light antenna with a homogenizer and an amplification system, and demonstrated its utilization in a four-spectrum mobile VLC. The central element is the homogenizer, which is a square integrating rod that mixes four-spectrum light into white light. Behind it, there are two Fresnel lenses to amplify the light-mixing area. The system is compact with a length of 80 mm and maximal diameter of 58.5 mm. We determined the initial structural parameters of the antenna by theoretical analysis, and then we determine the best parameters by simulation. Simulation results indicate that a 0.75 m×0.75 m area can be illuminated at 1.7 m distance. The detection surface has a high uniformity (76.27%), which can meet illumination and mobile communication requirements simultaneously.

1. Introduction
As a new generation of illumination sources, light emitting diodes (LEDs) have many advantages, such as environmental protection, high efficiency, low cost, and modulated performance. An LED-based VLC can illuminate a room and transmit data simultaneously, relieving the tension of a wireless spectrum. An indoor VLC has no radiation interference and is considered to be one of the most promising devices for use in wireless communication [1].

With the development of modulation and equalization technology, the single-channel VLC can already transfer data at Gbps rates. Devices have gradually developed into multi-channel VLC devices by using WDM technology [2-6]. Transmitting antennas, whether in a monochrome VLC system or a multicolor VLC system, are generally used to improve transmission distance or acquire suitable color temperature, illumination value, and high uniformity to meet the dual requirements of mobile communication. Until 2015, Wang Yiguang et al. [7] applied a reflection cup with 60° divergence angle to decrease the beam angle of RGB-LEDs for longer transmission distance. When combined with CAP modulation and equalization, an aggregate indoor free space data transmission rate of 4.5 Gbps was demonstrated over 1.5 m. In the same year, Wang et al. [8] used the same transmitting antenna, but the light source was changed to RGBY-LEDs. Then the data rate improved to 8 Gbps at 1 m. However, this optical antenna produces a color ring with low uniformity. With the development of multi-channel VLCS in 2016, Cui et al. [9] showed that a WDM-VLC system can transmit in up to 10 channels by theoretical analysis, i.e., the number of spectrum in an LED can be 10. In multi-colour WDM-VLC systems, the transmitting antenna plays a significant role in improving transmission...
distance, mixing color into an appropriate white light, and emitting highly uniform illumination for mobile communication and indoor illumination simultaneously.

This paper proposed a white light transmitting antenna for a mobile VLC system based on RGBY-LEDs, which consists of an integrating rod and two Fresnel lenses. The simulation and experimental results all show that our antenna achieved a suitable color temperature of 5583 K and a high uniformity of 73%. The structure of the system is compact and cheap, with 80 mm length and 58.5 mm maximum diameter.

2. Model of white light transmission antenna

2.1. Introduction of white light transmitting antenna

Like in Figure 1, an indoor VLC system based on RGBY-LEDs includes Uplink and Downlink. Uplink, that is, a transmitter, mainly includes an LED light source and a transmitting antenna. The transmitting antenna forms the uplink terminal and plays an important role in indoor illumination and mobile communication.

![Figure 1. Indoor VLC model system based on RGBY-LEDs.](image)

![Figure 2. (a) Arrangement and spacing of light sources and (b) white light transmitting antenna system](image)

According to indoor four-color WDM-VLC application demands and international illumination standards, we proposed the design standards of this white light transmitting antenna in Table 1. The illumination uniformity and chromatic aberration should both be considered for illumination demands and signal to noise ratio (SNR) stability in mobile communication.

| Parameter | Technical data specification |
|-----------|----------------------------|
| ![Table 1. White light transmitting antenna technical standards for a four-color VLC system](image) |
| waveband range         | 400 nm–760 nm |
|------------------------|--------------|
| illumination uniformity| ≥70%[10]     |
| chromatic aberration   | <0.005[11]  |
| communication distance | ≥1.75 m      |
| illumination area      | >0.5×0.5 m²  |
| illumination value     | 200-800 lx   |

2.2. System model and theoretical analysis of the transmitting antenna

At present, integrating rods and micro lens arrays are the most commonly used optical elements for reshaping a light beam for uniform illumination [12, 13]. A micro lens array can narrow the volume of the system, but incident light rays must be parallel, and the cost is high. The size of an integrating rod can be controlled. Incident parallel light rays are not required, and the cost is low. The light sources in our VLC system are LUXEON series Red (LXM2-PD01-0050), Yellow (LXML-PH01-0060), Green (LXML-PM01-0100) and Blue (LXML-PB02) (Philips) with 627 nm, 597 nm, 530 nm, and 470 nm peak wavelengths, respectively. These LEDs were arranged in a 2×2 array, as shown in figure 2 (a). Each LED has a similar large divergence angle. Thus, we used a square integrating rod.

The light mixing results from the integrating rod only appear in the output plane. If VLC system want to illuminate the room and transmit data at the same time, we should image the output plane in to obtain uniform illumination in a large area on the ceiling. This paper proposes a Fresnel lens design scheme. Compared with a traditional lens, Fresnel lenses is lightweight, and it facilitate system miniaturization. They also have large relative aperture, which can ensure energy efficiency. The entire system shown in figure 2 (b) can project a large illumination area at a far distance.

2.2.1. Integrating-rod model. The integrating rod can be either hollow or solid [14] and both rods will project beams with high efficiency and uniformity. A homogeneous N-BK7 solid rod was used in this study. The ray in the integrating rod travels under total internal reflection.

![Integrating rod and internal light path diagram.](image-url)

**Figure 3.** Integrating rod and internal light path diagram.
The end of the integrating rod
Fresnel lens
-l
l'
D'
d
Detecting surface

Figure 4. Schematic diagram of Fresnel lenses.

As shown in Figure 3, by using the image method, each reflection is equivalent to illumination by a virtual source. The color and illumination of the true and virtual sources are superposed on the output end of the rod, thus we can realize color mixing and high illumination uniformity. The total internal reflection times N is related to uniformity and can be expressed as

\[ N = \text{int}\left[\frac{1}{\sin \alpha} \frac{D}{D'} \right] \]  \hspace{1cm} (1)

where D and L are the diameter and length of the integrating rod, respectively, and \( \alpha \) is the refraction angle at the input end of the integrating rod.

N must be at least 5 if more than 70% illumination uniformity is desired [15]. A greater number of reflections results in better uniformity at the output end. Generally speaking, we can only increase N by increasing the length L, but light absorption losses will also increase. The value of L cannot be too large as a long rod inhibits minimization.

Relatively speaking, the value of D has a greater impact on energy utilization than uniformity. In non-imaging optics, the energy transmission between systems is typically described by the Etendue value. This parameter can be defined as:

\[ E_{\text{source}} = Kn^2 \pi \int \cos(\theta) dA d\Omega \]  \hspace{1cm} (2)

The Etendue of the light source (RGBY-LEDs) is defined as:

\[ E_{\text{source}} = Kn^2 \pi^2 \alpha \sin^2 \alpha (3A_{s1} + A_{s2}) \]  \hspace{1cm} (3)

In Eq. (3), \( n \) is the internal refractive index of the light source, and \( \alpha \) is LED’s divergence half-angle. RGY-LEDs have the same luminous area \( A_{s1} \), and the luminous area of the blue LED is \( A_{s2} \).

We can also calculate the Etendue of the rod’s output end using:

\[ E_{\text{rod}} = \pi A_r n_r^2 \sin \beta \]  \hspace{1cm} (4)

where \( n_r \) is the rod’s refractive index, \( A_r \) is the area of output end, and \( \beta \) is the effective ray incidence angle at the input end (\( \sin \beta = \sin \alpha / n_r \)).

The design is reasonable if \( E_{\text{rod}} > E_{\text{source}} \), and the energy utilization is proportional to \( E_{\text{rod}} \). In fact, the value of D is limited due to its influence on uniformity. Fresnel lenses are Etendue-limited systems, and they can only work effectively within a certain range of NA. Considering all these limitations, we found that D falls in the range 6 mm < D < 10 mm. Equation (1) was used to determine the range of L to be L > 44 mm.

2.2.2 Fresnel-lens model. According to the standard room model, we designed an amplification system using two identical Fresnel lenses, and the schematic diagram is shown in Figure 4.

The distance between the rod and the Fresnel lens I and the focal length of Fresnel lens \( f' \) can be calculated to be 14.16 mm < l < 23.60 mm, and 14.05 mm < f’ < 23.39 mm, respectively, according to Eq. (5):

\[
\begin{align*}
\frac{1}{l'} - \frac{1}{l} &= \frac{1}{f'} \\
\frac{1}{l} &= \frac{d}{d'}
\end{align*}
\]  \hspace{1cm} (5)
The transmission distance $l'$ is 1.77 m, and the length and width of the illumination area $D'$ are both 0.75 m.

We can now calculate that the focal length range of one Fresnel lens must be $27.60 \text{ mm} < f' < 46.07 \text{ mm}$ using Eq. (6)

$$\frac{1}{f'} = \frac{2}{f'^2} - \frac{d}{f'^2}$$

(6)

Where $d = 1$ mm is the distance between two Fresnel lenses.

### 3. Design and optimization of white light transmitting antenna

#### 3.1. Design of the white light transmitting antenna

According to the above values and the aforementioned standards, we optimized the design parameters for the white light transmitting antenna by ZEMAX. We found that an antenna with a square rod showed the best performance. We also designed an antenna with a hexagon rod as an example for comparison. The details are presented in Table 2.

| Parameter list of the white light transmitting antenna system |
|---------------------------------------------------------------|
| **Integrating rod**                                           |
| **Shape of the end**                                          |
| square hexagon                                               |
| **Side-length of input end (mm)**                             |
| 7 4.35                                                       |
| **Side-length of output end (mm)**                            |
| 7 4.35                                                       |
| **Length (mm)**                                               |
| 60 60                                                        |
| **Fresnel lens**                                              |
| **Material**                                                  |
| ACRYLIC                                                      |
| **Groove/inch**                                               |
| 232                                                          |
| **Diameter (mm)**                                             |
| 50.8                                                          |
| **Focal length (mm)**                                         |
| 51                                                           |
| **Thickness (mm)**                                            |
| 1.5                                                          |

In our design, each LED is placed next to the input end of the integrating rod, which can improve the efficiency and narrow the volume of the system. The distance between the rod and the Fresnel lens is 13.5 mm. The maximum diameter of the transmitter is 50.8 mm, and the total length is 80 mm.

#### 3.2. Simulation of the transmitting antenna

According to the ANSI-NAMP IT 7.228-1997 illumination standard, we used 9 points method to calculate the uniformity degree with the following equations:

$$E_{\text{ave}} = \frac{\sum_{i=1}^{n} E(i)}{n}$$

$$N_1 = \left[ 1 - \frac{E_{\text{max}} - E_{\text{ave}}}{E_{\text{ave}}} \right] \times 100\%$$

$$N_2 = \left[ 1 - \frac{E_{\text{min}} - E_{\text{ave}}}{E_{\text{ave}}} \right] \times 100\%$$

$$N = \min\{N_1, N_2\}$$

(7) (8) (9)
If we substitute the data shown in Figure 5 into Eq. (7) to (9), the value of $N_{square}$ was calculated to be 76.27%. Because of the limits of the simulation software, we cannot calculate an accurate value for the H-rod system. We can visually see that its uniformity is lower than that of the S-rod system. The efficiency of the S-rod and H-rod systems were 45.87% and 43.03%, respectively. The practical illumination value can be adjusted based on different demands.

4. VLC experiments with white light transmitting antenna

4.1. Illumination experiment with transmitting antenna

As shown in Figure 6, according to the above simulation design, we built a model machine for the white light transmitting antenna.

![Model machine of the white light transmitting antenna](image)

Figure 5. Detection surface: illumination distribution (lm)

We illuminated a square region with 75 cm side length and a hexagon region with 46 cm side length at a distance of 1.77 m in a darkroom just as shown in Figure 7. The experimental results are shown in Figure 8, which shows the true-color graph of the square integrating rod system (S-rod system) and the hexagon integrating rod system (H-rod system) by Monte Carlo ray tracing method.

![Schematic diagram of 9 points method](image)

Figure 6. Model machine of the white light transmitting antenna

Figure 7. schematic diagram of 9 points method.

![Actual illumination surface and illumination distribution (lx)](image)

Figure 8. Actual illumination surface and illumination distribution (lx)

We can calculate total illumination $E$ and the uniformity degree $N$ using Eqs. (7) to (9). The S-rod system showed the best performance. The experimental results agree well with the simulation results.

$$E_{square} = 224.15lx, E_{hexagon} = 194.34lx$$

(10)

$$N_{square} = 73.37\%, N_{hexagon} = 67.18\%$$

(11)

The color temperature of the detection surface is 5583 K. Compared with a white color coordination value of 5500 K (CIE color coordination system), the chromatic aberration is 0.0021, which is less than eye resolution (<0.005). Thus, the device is suitable for indoor illumination.
4.2. Mobile VLC experiment with transmitting antenna

The setup of the monochromatic VLC system is shown in Figure 9. We used a blue LED as an example, other LEDs’ results are similar with this blue LED because of the high uniformity of this system. We set up a VLC experimental link shown in Figure 9(b) with a 1.77 m communication distance. An arbitrary sine wave generator (Agilent N9310A) with frequency set to 170 MHz was used to set the data transfer rate to 340 Mbps. 25 points are evenly selected in the 9 equal-sized areas in order to verify the mobile VLC performance. In the block diagram, we moved the transmitting terminal using translation stages.

As shown in Figure 10, all signal are the same. As shown in Figure 11, the maximum voltage is 2.08 V. The minimum value is 1.86 V. Thus all values meet the 3 dB attenuation requirement.

![Figure 9. (a) Block diagram for mobile communication testing; (b) VLC experimental link.](image)

![Figure 10. Waveform graph](image)

![Figure 11. Peak to Peak value for each waveform](image)

5. Conclusion

We presents a white light transmitting antenna based on an indoor four-spectrum VLC system, which included a square integrating rod and a Fresnel lens system. This antenna mixes beams from an array of RGBY-LEDs into white light with high uniformity (73.37%) and projects the mixed beam into an illumination area of 0.75 m x 0.75 m at 1.77 m transmission distance. The CCT of the detection surface is 5583 K which is less than the value for an eye (<0.005).

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