。Czech Technical University

Prague Faculty of Electrical Engineering

Department of Electrical Power Engineering

Diploma Thesis

Application of laser for general lighting

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MASTER'S THESIS ASSIGNMENT

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Branch of study: **Electrical Power Engineering**

II. Master's thesis details

Master's thesis title in English:

Application of laser for general lighting

Master's thesis title in Czech:

Možnosti využití laseru pro všeobecné osvětlování

Guidelines:

1) Theory of transformation of monochromatic laser radiation into white light
2) Photometric properties of white light transformed from laser
3) Principles of transmission of information by laser and white light (Li-Fi)

Bibliography / sources:

[1] CIE 013.3-1995: METHOD OF MEASURING AND SPECIFYING COLOUR RENDERING PROPERTIES OF LIGHT SOURCES, ISBN 978 3 900734 57 2

[2] David L. DiLaura, Kevin Houser, Richard Mistrick, Gary Steffy: IES LIGHTING HANDBOOK 10th edition, ISBN: 978-0-87995-241-9

[3] Svilen Dimitrov, Harald Haas: Principles of LED Light Communications: Towards Networked Li-Fi, ISBN: 978-1107049420

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Date of master's thesis assignment: **15.02.2019** Deadline for master's thesis submission: **24.05.2019**

Assignment valid until: **20.09.2020**

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Czech Technical University in
Prague Faculty of Electrical
Engineering

Department of Electrical Power Engineering

DIPLOMA THESIS ASSIGNMENT

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Prague, February 22, 2019

Declaration

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In Prague on_________________________

Acknowledgement

I would like to thank everyone that were involved in the development of this thesis, especially my supervisor Ing.Marek Bálský, Ph.D. and Ing. Jan Kyncl, Ph.D. for their continuous guidance and support.

Možnosti využití laseru pro všeobecné osvětlování

Abstrakt:

Bílé světlo hraje velmi důležitou roli v lidském životě a v produktivitě na pracovištích. Světelný zdroj založený na polovodičovém laseru má výhody malé velikosti, nízké spotřeby energie, stabilní barvy světla a dlouhé doby života. Jedná se o novou generaci polovodičového světelného zdroje s dobrými vyhlídkami na rozvoj. Je velmi důležité provádět v této oblasti výzkum. Hlavním obsahem této práce je:
1. Diskuse o teorii transformace monochromatického laserového záření do bílého světla.Prostřednictvím principu míchání světla je diskutována možnost syntézy bílého světla z monochromatického laseru stimulací luminoforu.
2. Zaměřuje se především na způsob modrého polovodičového laseru a excitaci žlutého luminoforu, diskutuje fotometrické vlastnosti bílého světla transformovaného z laseru. Vliv složení a tloušťky luminoforu je simulován a analyzován softwarem Trace Pro.
3. Diskutovány jsou výhody a nevýhody LiFi komunikační technologie v porovnání s WiFi technologií. Dále jsou studovány komponenty LiFi a modulační technika pro LiFi.

Klíčová slova:

Polovodičový laser, bílé světlo, luminofor, Li-Fi technologie.

Application of laser for general lighting

Abstract

White light illumination plays a very important role in human life and production activities. The light source based on semiconductor laser white light illumination has the advantages of small size, low energy consumption, stable light color and long working life. It is a new generation of solid-state lighting source with good development prospects. It is of great significance to carry out research on it. The main contents of this paper are as follows:

1. Discussing the theory of transformation of monochromatic laser radiation into white light. Through the principle of light mixing, the possibility of synthesizing white light by monochrome laser stimulate the phosphor is discussed.
2. Mainly focuses on the way of the blue semiconductor laser to exciting the yellow phosphor, discuss the photometric properties of white light transformed from laser. The influence of the concentration and thickness of the light source are simulated and analyzed by Trace Pro software.
3. Comparing with WiFi technology, discuss the advantages and disadvantages of LiFi communication technology. Moreover, the LiFi components and modulation technique for LiFi are studied.

Keywords:

Semiconductor laser, white light, phosphor, Li-Fi technology.

Contents

1. Introduction

In recent years several research groups and lighting manufacturers have been working toward the development of higher efficacy light sources, with higher luminous performance and improved optical management, aiming at possible ways for new applications.

Over the last fifteen years, gallium nitride (GaN)-based light emitting diodes (LEDs) have been demonstrated to be excellent light sources, and—thanks to the intensive research effort—they have changed from an early technology (in the late 90s) to a mass product with record efficacies in excess of 300 lm/W [1]. Nowadays GaN-based LED technology is widely used for homes, cars, streets, and many other applications.

GaN-based LEDs emit monochromatic violet, blue or green radiation depending on the alloy composition; the use of phosphorescent materials (based on garnets, aluminate or silicate doped with rare earths), allows the conversion of the short-wavelength radiation emitted by the LEDs into a broad yellow–green spectrum, thus permitting the generation of white light.

While a relevant research effort is still being carried out to increase the performance of GaN LEDs, new research fields are being explored, with the aim of solving some of the technological limitations of LED lighting.

One of these fields is solid state laser lighting, which is potentially showing several advantages over LED technology. The basic idea is to create white light sources based on GaN-based laser diodes, instead of using the conventional GaN LEDs.

The reason the use of a semiconductor laser might be interesting for general lighting is not the stimulated coherent emission typical of a laser, but the high light intensity, luminous efficiency and optical management of the light beam.

The aim of this paper is to describe the application of laser for general lighting. The first part of the paper presents the theory of transformation of monochromatic laser radiation into white light; the second part of the paper reports Photometric properties of white light transformed from laser. In the last part of the paper, we discuss principles of transmission of information by laser and white light (Li-Fi).

2. Introduction of laser

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "Light Amplification by Stimulated Emission of Radiation" [2].

A laser differs from other sources of light in that it emits light coherently. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers and lidar. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single color of light. Alternatively, temporal coherence can be used to produce pulses of light with a broad spectrum but durations as short as a femtosecond ("ultrashort pulses").

2.1 Theory

The state of motion of electrons can be divided into different energy levels. When electrons transition from high energy level to low energy level, electromagnetic waves of corresponding energy are released (so-called spontaneous radiation). In the typical illuminant, the action of electrons to emit photons is random and the emitted photons do not have the same characteristics, such as the light emitted by a tungsten lamp.

When applied energy is injected into and absorbed by an energy level system by electric field, photon, chemistry, it will cause electrons transition from low energy level to high energy level. When photons generated by spontaneous radiation meet these electrons, these high-energy electrons are induced to move to lower energy levels and emit photons (so-called stimulated radiation). All optical characteristics of the stimulated radiation will be same as the original spontaneous radiation, like frequency, phase and direction. When these photons of stimulated radiation encounter other electrons that jump to high energy levels due to the applied energy, they will produce more same photons and finally, the intensity of the light is getting larger and larger (that is, the light energy is amplified). Unlike ordinary light, all photons have the same frequency, phase (coherence) and direction of advancement [3].

To achieve light amplification, it is necessary to create an environment with a higher number of high-energy electrons than low-energy electrons, that is, the population inversion. So that can let high-energy electrons encounter the photon to release new photons instead of randomly releasing them.

2.2 Design

A general laser generator has three basic elements:

Pumping source: also known as the "pump source", which supply energy to low-level electrons and excited them to become high-energy electrons. The energy supply methods include charge discharge and chemical action.

Gain medium: the substance in which electrons that are excited and emitted located. Their physical properties affect characteristics such as the wavelength of the generated laser.

Optical cavity/optical resonator: They are mirrors that are parallel to each other, with a total reflection on one side and a half reflection on the other. The purpose is to reflect the light back and forth between the mirrors, in order to let the excited light obtain sufficient amplification via pass through the gain medium multiple time. So that the laser could be emitted from the half reflection mirror [4].

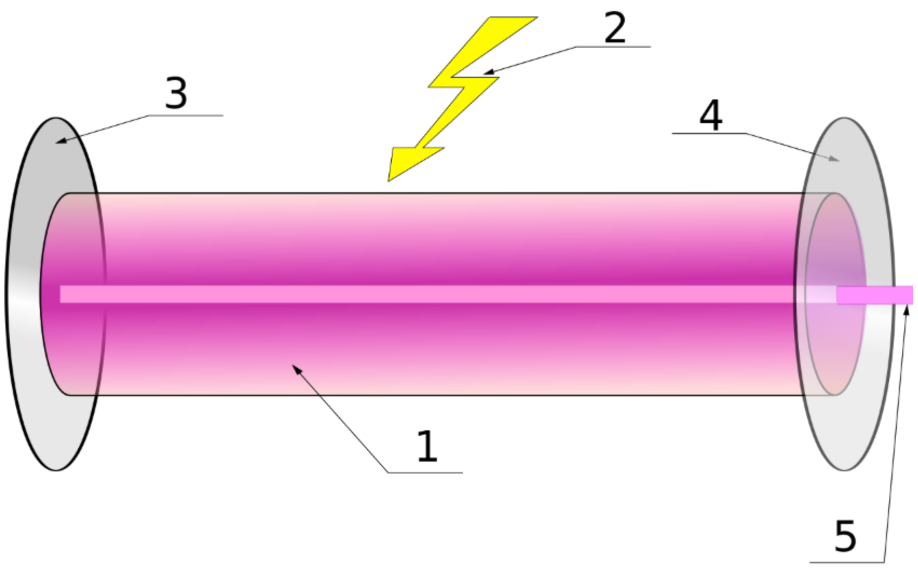


Figure 1. Components of a typical laser [5]

Components of a typical laser:

1. Gain medium

2. Laser pumping energy

3. High reflector

4. Output coupler

5. Laser beam

2.3 Stimulated emission

The process in which an incident photon of a specific frequency interacts with an excited atom and then descends to an incident photon of a lower energy level is stimulated emission. When the released energy was transferred to the electromagnetic field, new photons with not only the same phase, frequency, polarization, but also the direction of travel with the incident wave are generated. Therefore, stimulated emission is different from spontaneous emission, because spontaneous emission does not take the ambient electromagnetic field into account and occurs at random intervals. For example, laser light which is common in our daily life is a kind of radiation originating from stimulated emission.

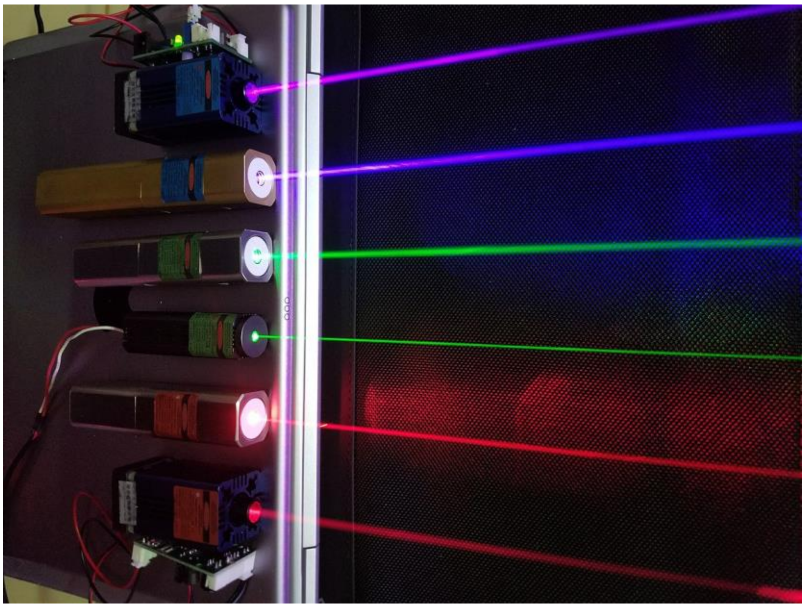


Figure 2. Different color of lasers [5]

2.3.1 Overview

In the classical view, the energy of an electron orbiting an atomic nucleus is larger for orbits further from the nucleus of an atom. However, quantum mechanical effects force electrons to take on discrete positions in orbitals. Thus, electrons are found in specific energy levels of an atom, two of which are shown below

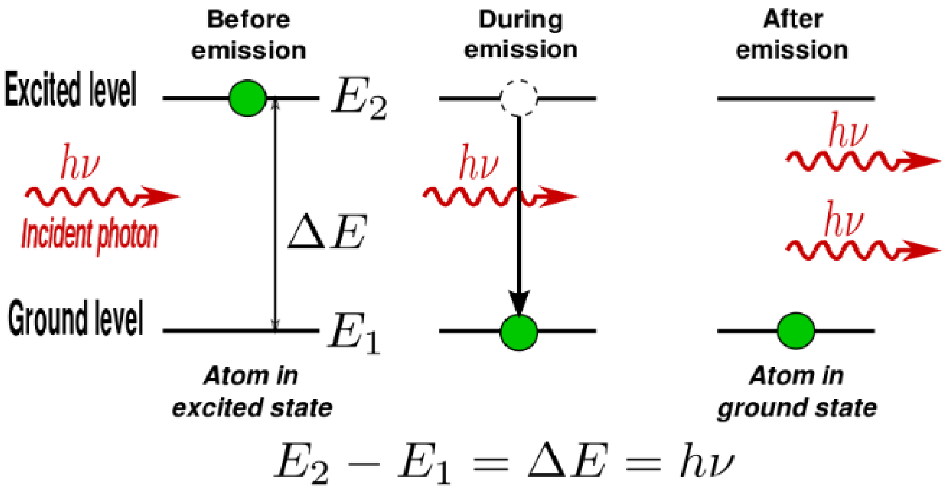


Figure 3. two energy levels of an atom [6]

The electrons can change their orbit by energy level transitions. The orbits which are farther away from the nucleus have higher energy levels. Photons are emitted when electrons transition from orbits (higher levels) farther away from the nucleus to orbits (lower levels) closer to the nucleus. Conversely, the absorption of photons or phonons allows electrons to transition from lower energy orbits to higher energy orbits. Each transition corresponds to a specific energy and wavelength [6].
A lower level state and an excited state, with energies E1 and E2 corresponding to the transition satisfy the relationship:

$$E_2 - E_1 = hv = \frac{hc}{\lambda}$$

Where c is speed of light in vacuum, $\mathbf{c} = 3 \times \frac{10^8 m}{s}$, λ is the wavelength, v is the frequency and h is Planck's constant equal to 6.62×10^{-34}J·s.

2.3.2 Stimulated emission transition probability

Normally, most of the particles are in the ground state. In order for these particles to radiate, it is necessary to excite the particles in the ground state to the high energy level. Because of the different internal structure of atom, the same external conditions make the probability of atom excitation from ground state to each high level different. The possibility of exciting an atom, molecule or ion to a certain level is usually called the " Transition Probability " of this level.

Let the density of the number of particles on the high-level E_2 at time t be N_2 (t) and the energy density of the monochromatic radiation of the incident light with frequency v be ρ_v. The number of particles dN_{21} that transit from the high-level E_2 to the low-level E_1 in the unit volume of time t to t+dt is as follows:

$$dN_{21} = B_{21} N_2 \rho_v dt$$

B_{21}, known as the stimulated emission coefficient, is a characteristic parameter of the particle level system. If $W_{21} = B_{21}\rho_v$, we can get

$$W_{21} = B_{21}\rho_v = \frac{dN_{21}}{dt} \times \frac{1}{N_1}$$

W_{21} is defined as the ratio of the number of atoms in the N_2 high-energy atoms that transitioned to the low-energy due to stimulated emission to N_2 per unit time. That is, the probability that each particle at E_2 level be stimulated in a unit time. So W_{21} is called stimulated emission transition probability [6].

2.4 Application of laser

Lasers are used in optical disk drives, laser printers, barcode scanners, DNA sequencing instruments, fiber-optic and free-space optical communication, laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in laser lighting displays for entertainment. They have been used for car headlamps on luxury cars, by using a blue laser and a phosphor to produce highly directional white light [7].

3. Theory of transformation of monochromatic laser radiation into white light

3.1 White laser

White laser is a kind of illumination light source technology based on laser to produce high luminance white light

Strictly speaking, "monochromaticity" is one of the basic characteristics of laser, so laser cannot be white, because "white" and "monochromaticity" are contradictory. The so-called "white laser" is a kind of illumination technology that uses monochrome laser to convert white light. Because of the use of laser as energy sources, white lasers are naturally endowed with laser genes, which are characterized by high luminance and high collimation.

Nobel Prize winner and inventor of white LED Shuji Nakamura predicts that laser lighting (the scheme of converting monochrome laser into white light using phosphor materials) will replace LED lighting as a new generation of lighting technology in the future [8].

But unlike white LED, the phosphor material in white laser needs to withstand more than 10 times of the intensity of laser bombardment. Only in this way can the white laser source with much higher intensity than white LED be realized. If ordinary phosphor materials for LED are used, they will be blackened instantly by their own heating under laser excitation. Therefore, this kind of white laser has higher requirements in material technology. The laser lamp of BMW I8 is made with this kind of white laser technology.

3.1.1 Advantages and disadvantages.

3.1.1.1 Advantages:

a) Only one laser source is used so the cost is low. Of course, it is still much higher than the LED, but it can achieve the remote illumination function that the LED cannot achieve and it is more suitable for some special applications.

b) Because of the phosphor conversion of laser, the speckle and coherence of laser itself are completely eliminated which is no laser speckle phenomenon.

c) In the process of white laser conversion, most of the laser energy is converted into broad-spectrum light and the luminous angle increases obviously, which make it is safer than pure laser and more suitable for some civil occasions [9].

3.1.1.2 Disadvantages:

a) The collimation of white laser is worse than laser due to the increase of luminous angle during white laser conversion.

b) In the process of white laser conversion, a large amount of fluorescent stray light is produced, which needs to be dealt with in the optical processing of the back-end [9].

3.1.2 Application of white laser.

White laser has the characteristics of high luminance and collimation similar to laser, which cannot be replaced by white LED. However, the price of white laser is much higher than white LED, so white laser is more suitable for those occasions where white LED is not competent. Of course, with the formation of industrialization and the gradual decline of laser prices, the price of white laser has been in a downward trend. One day it will compete with white LEDs in the general lighting market.

White lasers have the following applications [10]:

a) Special lighting. For example, stage beam lamp, remote searchlight and digital projection.

b) Vehicle lighting. Including automobile headlamp and long-range auxiliary lighting.

c) Medical lighting. Application of speculum illuminator.

3.2 Approach to get white laser.

General lighting systems produce white light; from monochromatic sources (like LEDs and laser diodes, LD) white light can be obtained through the red-green-blue (RGB) approach, or via phosphor conversion. Due to higher color rendering performance, global efficiency and thermal stability, phosphor conversion is the most used method in the lighting industry. White light is therefore generated starting from a blue light source, typically with a peak wavelength of 440–460 nm, which is then partially converted into a broader emission coming from the phosphors [11].

Normally, white light source can be obtained by three methods:

1) White light is synthesized by mixing multi-color laser;

(2) White light is synthesized by exciting red, green and blue phosphors by near-ultraviolet laser;

(3) Blue laser excites yellow phosphor to synthesize white light.

3.2.1 White light synthesis by multicolor laser mixing

This method synthesizes white light by using three-color (red, green, blue) semiconductor lasers or four-color (red, green, blue, yellow) semiconductor lasers. As shown in Figure 4, white light with different color (such as different color index, color temperature) can be obtained by controlling the power output of each laser.

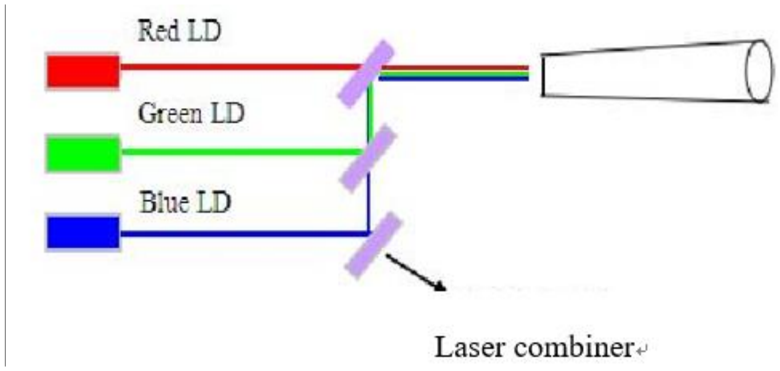


Figure 4. White Light synthesized by Tri-Primary LD Laser [12]

Advantages: Because no phosphor is used, so there is no Stokes loss produced by phosphor and its electro-optic conversion efficiency is relatively high.

Disadvantage: This method requires multiple lasers so costs a lot. Secondly, the driving circuit is complex because the ratio of output power of different lasers is controlled to synthesize white light source suitable for illumination. Meanwhile, the energy density per unit area of the laser is very high and there may be appear leakage of the laser in the use process, which has potential safety hazards. In addition, the light attenuation rates of different lasers are different, which may change the color characteristics of the light source and affect the stability of the light source [12].

3.2.2 Polychromatic phosphors excited by near-ultraviolet laser

This method is use blue and yellow phosphors excited by near-ultraviolet laser diodes to synthesize the white light. The principle of this method is that the blue phosphor first absorbs the laser and converts the laser beam into blue light. Then the blue light passes through the Yellow phosphor. The yellow phosphor converts part of the blue light into yellow light. Finally, the yellow light mixes with the blue light which is not converted by the yellow phosphor into white light.

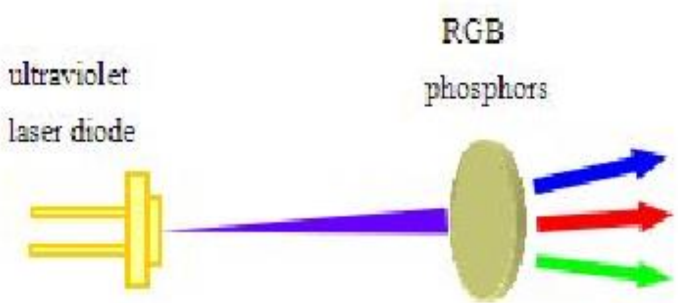


Figure 5. Ultraviolet LD stimulate RGB phosphors [12]

In addition, white light can be obtained by stimulating red, green and blue phosphors with near-ultraviolet laser diodes. Figure 5. is the schematic diagram. This method mainly uses near-ultraviolet laser to stimulate triple-color phosphors to obtain corresponding red, green and blue triple-color light and finally mixes the output white light.

Advantages: Firstly, this method uses only one laser so its cost is lower than that of white light synthesized by polychromatic laser. Secondly, when the laser excites the phosphor, the phosphor particles absorb, refract and reflect the laser before entering the outside world. At this moment, the light is no longer a high energy density laser, so it is safer to the human eye. Thirdly, the white light synthesized by this scheme has high color rendering index, good color reduction and better lighting effect.

Disadvantage: The use of phosphors can cause Stokes loss, resulting in lower photoelectric conversion efficiency than when white light is synthesized directly by a polychromatic laser. Moreover, the decay rates of various phosphors used are different, which will cause the fluctuation of color temperature of white light source.

3.2.3 Blue laser stimulate yellow phosphor.

In the method of synthesizing white light by using blue laser diode to stimulate yellow phosphor, part of blue light passes through directly without encountering phosphor particles, part of blue light is absorbed by phosphor and converted into yellow light emission, part of blue light is absorbed by phosphor particles and converted into heat energy, and part of blue light is scattered by phosphor particles. After these effects, the white light is mixes by the blue light which pass through the phosphor and the yellow light. As shown in Figure 6.

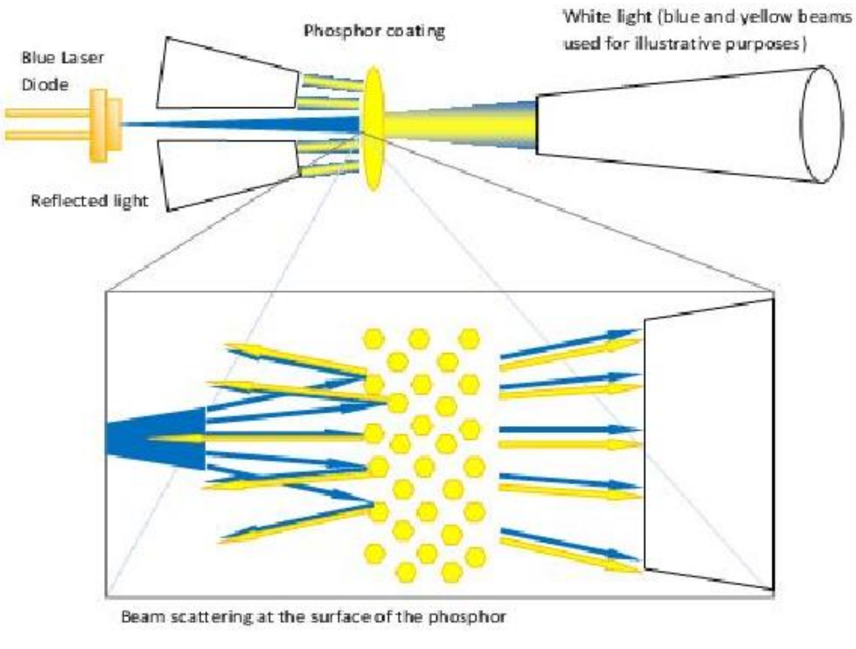


Figure 6. Synthesis of White Light from Yellow Phosphor Excited by Blue LD [12]

Advantages: This method only uses yellow phosphors. Compared with other phosphors, it has less Stokes loss and higher luminous efficiency. At the same time, the scheme of bombarding yellow phosphor with blue light is more stable than that of using multi-color phosphor. In addition, this method has simple structure and low cost, which is suitable for batch production.

Disadvantage: Because of the lack of red light spectrum in the spectrum, the color rendering of the light source synthesized by this method is not very well [12].

In view of the above analysis, compared with the other two methods, the method of blue LD stimulates yellow phosphor to synthesize white light is simple and the cost is relatively low. Although its color rendering index is low, red phosphor can be added to improve the color rendering of the light source according to the lighting requirements. So this paper choose the method of blue LD stimulates yellow phosphor to synthesize white light.

3.3 Development status and application of white light stimulated by laser.

3.3.1 Development Status of Semiconductor Laser White Light Source

In 2005, the first semiconductor laser white light source was born. As shown in Figure 7, the researchers of Nichia Company in Japan used optical fiber coupling method, than the white light is obtained from yellow phosphor excited by blue light from Ga-N-based semiconductor lasers [13].

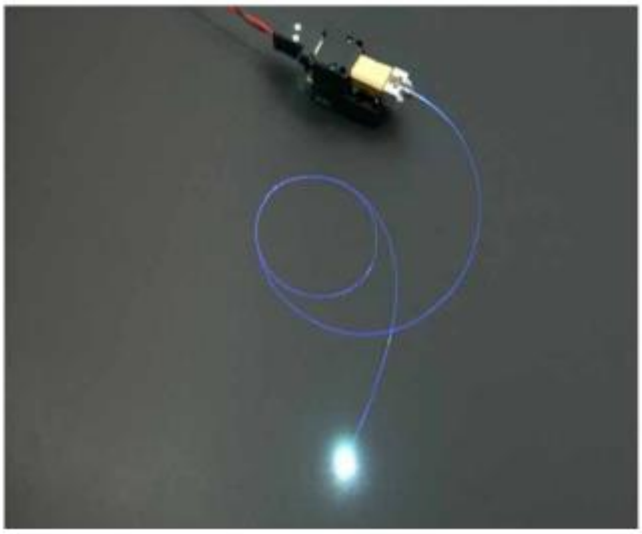


Figure 7. Nichia's First White Laser Light Source [13]

In 2008, S. Sailo from Japan used 405 nm laser to excite phosphors and realized a white laser source with 200 lm light flux [14].

In 2010, Han-Youl Ryu of Renhe University in Korea synthesized white light by using blue LD exciting yellow phosphor. They coupled the laser emitted by InGaN blue LD into a 400m optical fiber and the other end is coated with yellow phosphor, and finally, they got the 5 lm, 101m/w white light from yellow phosphor stimulated by the coupled output laser. Figure 8. is the emission spectrum of a white light source when the injection current is 40mA [15].

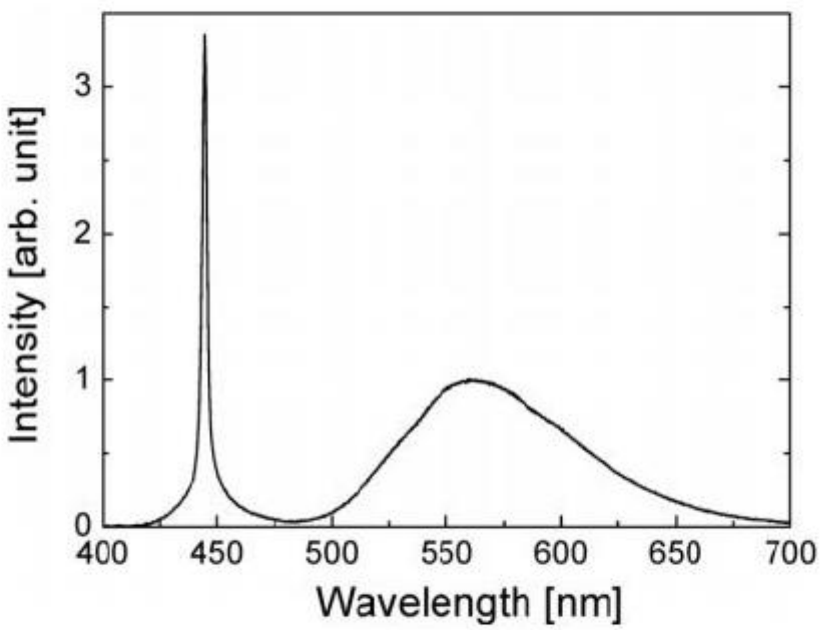


Figure 8. Emission spectrum of white light [15]

In 2013, Kristin from the University of California, USA, used near-ultraviolet LD to excite RGB (red, green, blue) phosphors with three primary colors, and finally obtained two kinds of white light sources with different light-color parameters. The light-color parameters of the first white light source are: correlation color temperature 3600 K, luminous flux 91 lm, luminous efficiency 16 lm/W and color rendering index 91. The second white light source are: correlation color temperature 2700 K, luminous flux 53 lm, luminous efficiency 19 lm/W and color rendering index 95 [16]. Figure 9. shows that white light with different color characteristics obtained from RGB phosphors excited by near-ultraviolet LD.

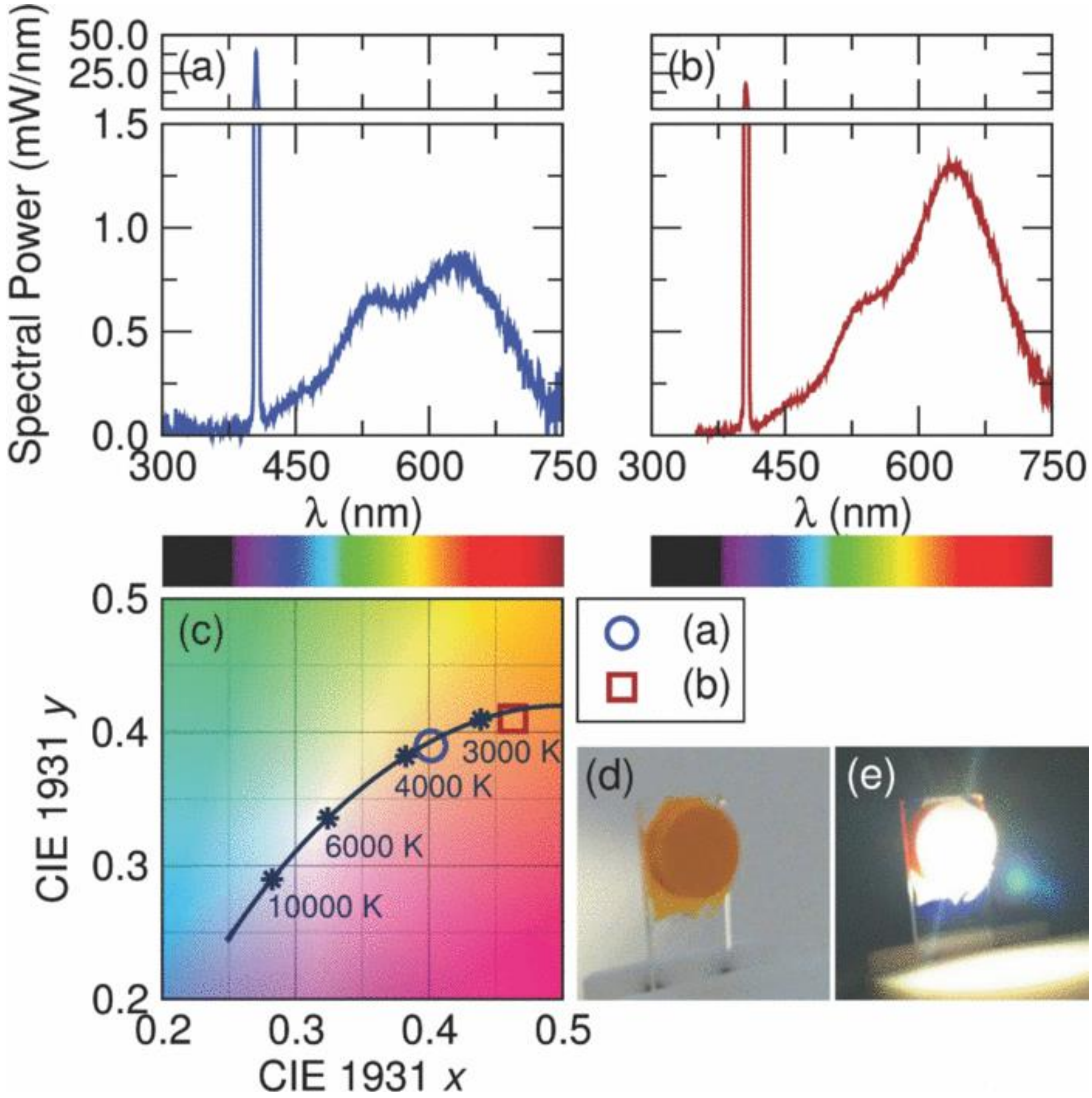


Figure 9: Spectral power distribution (SPD) for phosphor samples (a) RGB1 and (b) RGB2 excited using a near-UV (λ_{max} = 402 nm) laser diode and (c) the corresponding Commission Internationale de l'´Eclairage (CIE) chromaticity coordinates show white light with a variety of color temperatures is attainable. Photographs of the RGB2 phosphor sample (d) without and (e) with laser excitation. [16]

Kristin also used blue LD to stimulate the yellow Yttrium Aluminium Garnet (YAG) phosphors to obtain white light. The light-color parameters are: correlation color temperature 4400 K, luminous flux 252 lm, luminous efficiency 76 lm/W and color index 57 [16]. The figure 10. shows a comparison of the simulated and experimental photochromic properties of blue LD-stimulated yellow phosphor to obtain white light.

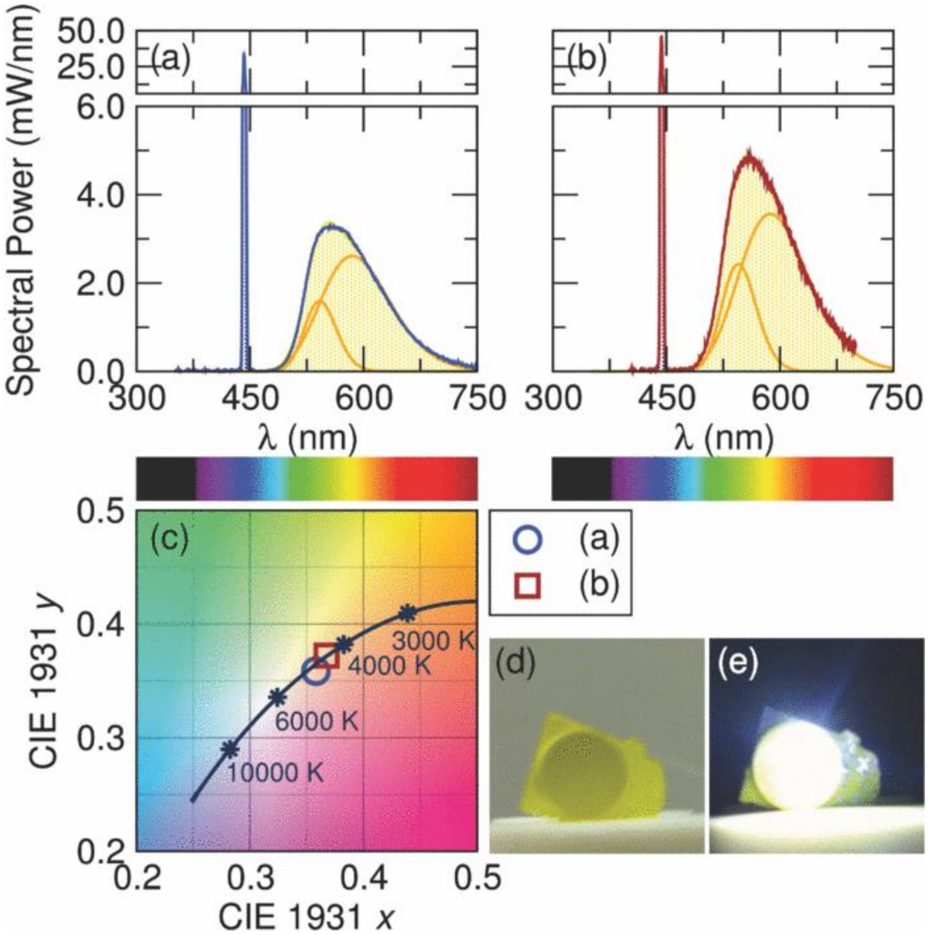


Figure 10: (a) Calculated SPD for target white light composed of YAG:Ce and a blue laser diode, (b) experimentally measured SPD with a similar ratio of laser to phosphor emission as that of the calculated SPD, (c) the corresponding CIE chromaticity coordinates, and a photograph of the YAG:Ce phosphor sample (d) without and (e) with laser excitation. The SPDs show the fits to three Gaussian curves, representing the fraction of emitted white light from laser emission and phosphor emission. [16]

In 2014, G. Ledru of the University of Toulouse, France, realized white light output by using blue laser diodes to excite phosphors at long distances. The experimental results show that the white light with color temperature of 4000K and color development index of nearly 95 is obtained [17].

Figure 11. Blue Laser Diode stimulate Phosphor [17]

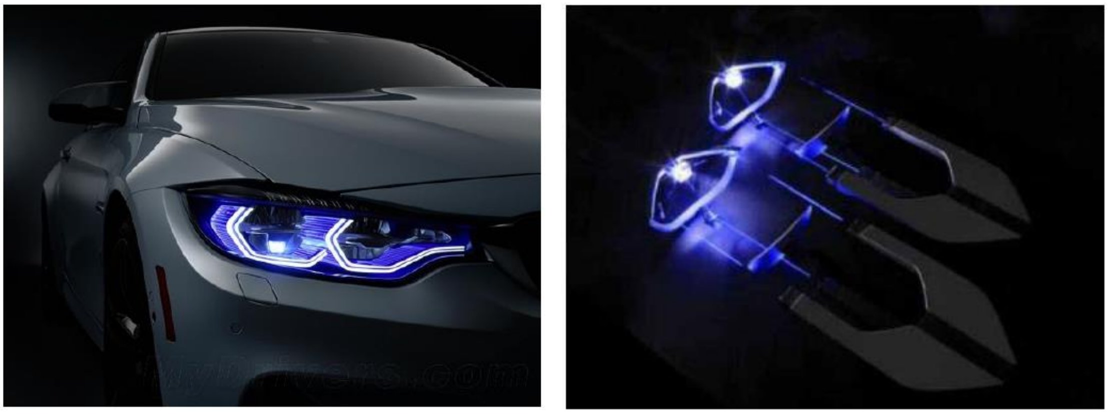
3.3.2 Application of Semiconductor Laser White Light Source

At present, the white light illumination technology of semiconductor laser has been applied in the field of car headlamp illumination. The performance has been recognized and remarkable results have been achieved. At present, the white light illumination technology of semiconductor laser has been applied in the field of car headlamp illumination, and its excellent performance has been recognized, with remarkable results. As a solid-state environmental protection light source, semiconductor lasers have high luminance, high luminous efficiency, smaller volume and high conversion efficiency under high current density, which ensures the high efficiency of lighting source and the stability of light color. It makes the lighting distance of automobile headlights farther and improves the driving safety of automobiles.

In the field of lighting, the output of car light source accounts for about 10% of the total output of lighting source, and its lighting source has experienced great development in the evolution of more than 130 years. The development of car headlight sources has mainly experienced the following generations: (1) acetylene gas combustion light source; (2) incandescent light source; (3) halogen light source; (4) hernia light source; (5) LED light source; (6) LD light source.

Compared with traditional automotive headlights, laser headlights have the following advantages: (1) lower energy consumption, lower luminance attenuation, faster reaction speed, longer life and higher lighting efficiency; (2) smaller size of laser headlights assembly, leaving more design space for stylists in the design of automotive front modeling; (3) longer illumination range of laser headlights. It can reach 500-600 m; (4) Laser headlamp can solve the problem of light heating and weight better.

The first laser headlamp application is Bayerische Motoren Werke (BMW) in German. BMW launched the first plug-in hybrid sports car BMW I8 with laser headlamp in 2011, which is the first mass-produced vehicle in the world to use laser headlamp technology. As shown in Figure 12, it is a BMW laser headlamp and its working principle. Its working principle is that three laser beams are reflected by a mirror and then incident on a yellow phosphorus filter to generate white light. Finally, the white light is reflected by the reflecting bowl to form an elliptical spot. At present, BMW's laser headlights can only be turned on at more than 40 km/h, and will be turned off when the car slows down or collides [18].



(a) (b)

Figure 12. BMW headlamp (a) BMW laser headlamp;

(b) BMW laser headlamp schematic diagram. [18]

3.4 Principle analysis of laser white light source

3.4.1 Study on blue and yellow light mixing.

3.4.1.1 Principle of Three Primary Colors.

According to the theory of three primary colors, any given color can be mixed with three primary colors (red, green and blue) in a certain proportion. Whether the three primary colors can be mixed into different colors is closely related to the selection of the three primary colors. The selection of three primary colors mainly follows the following rules. Firstly, no one of the three primary colors can be made by mixing the other two colors. Secondly, the three primary colors can mix as many colors as possible. Therefore, 700 nm red, 546.1 nm green and 435.8 nm blue are usually defined as three primary colors. When the ratio of red, green and blue is 10:45:6, white can be matched. Figure 13. shows a diagram of three primary colors [19].

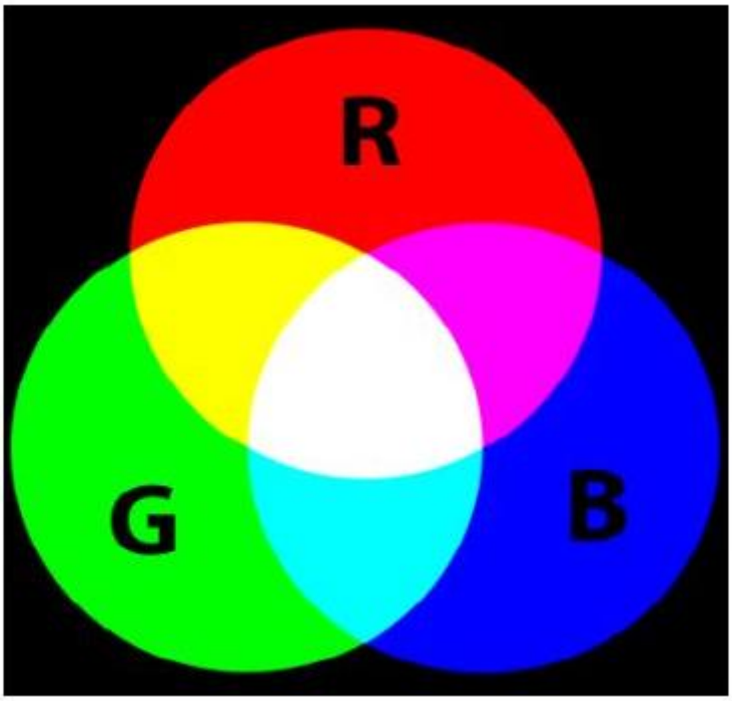


Figure 13. Schematic diagram of three primary colours matching [19]

In color matching, specific colors can be matched by a certain number of three primary colors. Generally speaking, the amount of three primary colors needed to match a certain color is the tristimulus values of that color. For a given three primary colors, the tristimulus values of each color are uniquely determined. Therefore, color can be expressed by tristimulus values [20].

If there were (C_1) and (C_2) are mixed, the color (C_1) and (C_2) can be expressed by tristimulus values according to color matching. Assuming that the tristimulus values of color (C_1) and (C_2) are R_1, G_1, B_1 and R_2, G_2 and B_2 respectively, the two color equations are:

$$(C_1) = R_1(R) + G_1(G) + B_1(B) \tag{3.1}$$

$$(C_2) = R_2(R) + G_2(G) + B_2(B) \tag{3.2}$$

The mixed color (C) formed by mixing the two colors is:

$$(\mathrm{C}) = (C_1) + (C_2) \tag{3.3}$$

According to the law of substitution, there are,

$$\begin{aligned}(\mathrm{C}) &= (C_1) + (C_2) \\ &= [R_1(R) + G_1(G) + B_1(B)] + [R_2(R) + G_2(G) + B_2(B)] \\ &= (R_1 + R_2)(R) + (G_1 + G_2)(G) + (B_1 + B_2)(B)\end{aligned} \tag{3.4}$$

Color (C) can also be expressed by tristimulus values R, G and B:

$$(\mathrm{C}) = \mathrm{R}(\mathrm{R}) + \mathrm{G}(\mathrm{G}) + \mathrm{B}(\mathrm{B}) \qquad (3.5)$$

Contrast (3.4) and (3.5), we can get

$$\mathrm{R} = R_1 + R_2 \,; G = G_1 + G_2 \,; B = B_1 + B_2 \qquad (3.6)$$

The above formula shows that the tristimulus values of mixed colors are the sum of the tristimulus values corresponding to each component color. This is the principle of color addition.

Obviously, the above principle can be extended to multi-color mixing. For n-color mixing, the tristimulus value of mixed color is:

$$\left.\begin{aligned} \mathrm{R} &= R_1 + R_2 + \cdots + R_n = \sum_{i=1}^{n} R_i \\ \mathrm{G} &= G_1 + G_2 + \cdots + G_n = \sum_{i=1}^{n} G_i \\ B &= B_1 + B_2 + \cdots + B_n = \sum_{i=1}^{n} B_i \end{aligned}\right\} \qquad (3.7)$$

Any color can be regarded as a mixture of spectral colors in different proportions. For the tristimulus values dR(λ), dG(λ), dB(λ) of light (central wavelength is λ and the range of microwave interval is dλ), since it is proportional to the color stimulus function $\varphi(\lambda)$, the corresponding spectral tristimulus values $\bar{\mathrm{r}}(\lambda), \bar{\mathrm{g}}(\lambda), \bar{\mathrm{b}}(\lambda)$ and the wavelength interval dλ, the following relationships can be obtained:

$$\left.\begin{aligned} d\mathrm{R}(\lambda) &= \mathrm{k}\varphi(\lambda)\bar{\mathrm{r}}(\lambda)\mathrm{d}\lambda \\ \mathrm{dG}(\lambda) &= \mathrm{k}\varphi(\lambda)\bar{\mathrm{g}}(\lambda)\mathrm{d}\lambda \\ \mathrm{dB}(\lambda) &= \mathrm{k}\varphi(\lambda)\bar{\mathrm{b}}(\lambda)\mathrm{d}\lambda \end{aligned}\right\} \qquad (3.8)$$

We can via integral the above formula to obtain the tristimulus values of all spectral color mixtures in the whole visible spectrum range:

$$\left.\begin{aligned} \mathrm{R} &= \mathrm{k}\int_0^{\lambda} \varphi(\lambda)\,\bar{\mathrm{r}}(\lambda)\mathrm{d}\lambda \\ \mathrm{G} &= \mathrm{k}\int_0^{\lambda} \varphi(\lambda)\,\bar{\mathrm{g}}(\lambda)\mathrm{d}\lambda \\ \mathrm{B} &= \mathrm{k}\int_0^{\lambda} \varphi(\lambda)\,\bar{\mathrm{b}}(\lambda)\mathrm{d}\lambda \end{aligned}\right\} \qquad (3.9)$$

For light source color, the color stimulus function is $\varphi(\lambda) = \mathrm{S}(\lambda)$. $\mathrm{S}(\lambda)$ is spectral sower sistribution of light source [21].

3.4.1.2 CIE Color System

In modern lighting technology, the requirement of color effect is getting higher and higher. If we only use everyday language (such as red, bright red, purple red, etc.) to describe color, it will often cause inaccurate conclusions because of people's different senses. In order to calibrate the color accurately, the color system is usually used. The most commonly used color system is 1931CIE-XYZ color system, which is based on the theory of three primary colors. It can not only accurately calibrate the color, but also quantitatively analyze the additive mixing of light and color. Figure 14. is the chroma diagram of 1931 CIE-XYZ system [22].

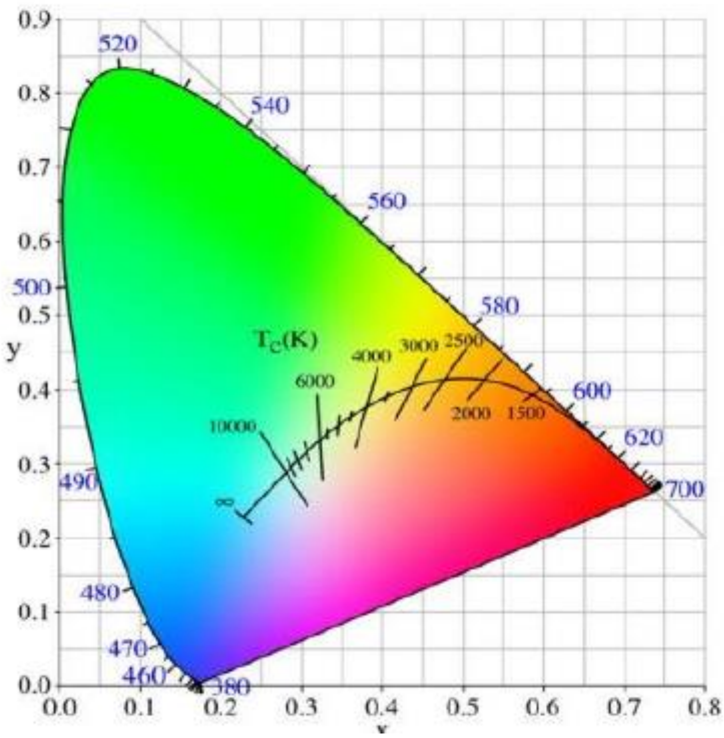


Figure 14. The chroma diagram of 1931 CIE-XYZ system. [22]

According to the above principle of light mixing, blue and yellow color can match white color. Therefore, this paper uses the method of mixing blue and yellow light to synthesize white light. For example, in the CIE 1931 chromaticity diagram of the following Figure 15, point A represents the light of blue wavelength and point B represents the light of yellow wavelength. According to the principle of light mixing, all colors on the line between A and B can be matched by A and B.

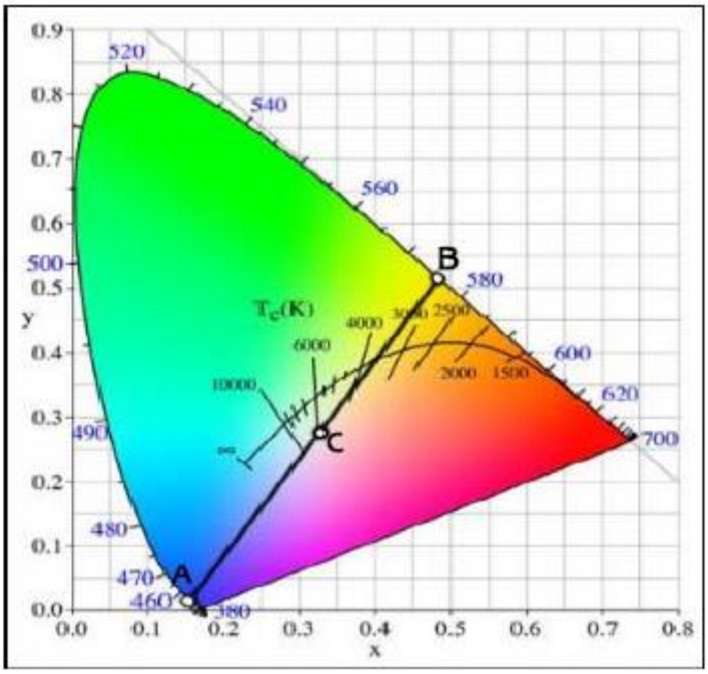


Figure 15. The chroma diagram of 1931 CIE-XYZ system [54]

According to Figure 15, we can find that white light at point C can be obtained by adjusting the ratio of A and B light, which is specifically expressed as:

$$\mathrm{C(color)} = \mathrm{n} \times \mathrm{A(blue)} + (1 - \mathrm{n}) \times \mathrm{B(yellow)} \qquad (3.10)$$

In the formula, n is the proportion of blue light. Various light sources of color temperature can be obtained by adjusting the size of n.

3.4.2 Selection of Semiconductor Lasers

Since the advent of semiconductor lasers, after 50 years of development, its laser band has developed from infrared and red bands to green, blue, near-ultraviolet and ultraviolet bands. Since Na Kamura realized the first blue-light semiconductor laser, visible-light semiconductor lasers have been widely used in display, lighting and storage [6]. At present, the output power of red and blue laser diodes has reached watt level, and the output power of near-ultraviolet laser diodes has been greatly improved compared with that of ten years ago.

According to the experimental scheme selected in this experiment, white light output can be achieved by using blue laser diode to excite yellow phosphor. “MLD-450-1400” laser diode is selected in this paper. Its peak wavelength is 447 nm, color coordinate x=0.159, y=0.015, fast axis divergence angle θ_f ≤25°, slow axis divergence angle θ_l ≤15°. Emission spectra of LD is shown in Figure 16.

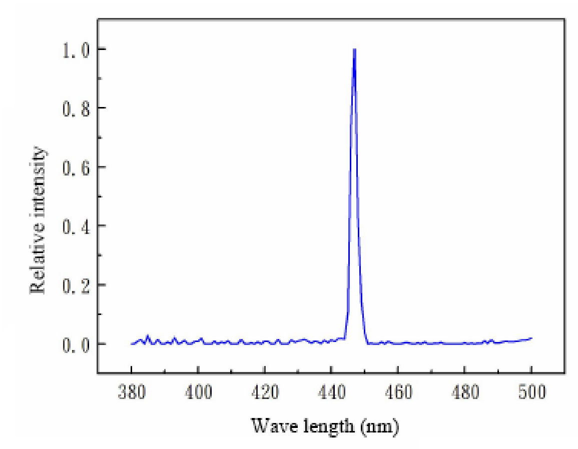


Figure 16. Emission Spectrum Chart of Laser Diode [54]

3.4.3 Selection of phosphors.

Phosphors are widely used in white LED lighting, fluorescent lamp and electroluminescence. At present, commercial phosphors are mainly divided into four categories: aluminate phosphors, silicate phosphors, nitrogen (oxygen) phosphors and sulfide phosphors.

Ce is mostly used as dopant in aluminate phosphors. At present, the most widely used and representative one is YAG: Ce. The emission peak width, chemical stability, high accident temperature and low corrosivity of aluminate phosphors are discussed. However, the red component of the phosphor is relatively small and its color rendering is poor.[23] We can increase the red light component of phosphor and improve the color rending of phosphor by mix Pr, Gd and Sm in YAG: Ce [24].

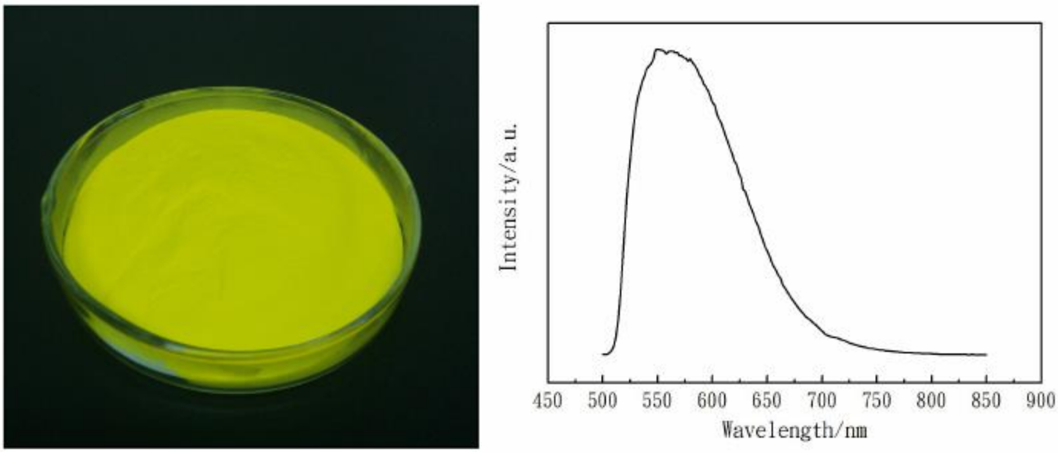
The excitation band of Silicate Phosphors is wide (200-500 nm) and the emission wavelength range is wide (507-610 nm). However, the chemical properties of silicates at high temperature are unstable and their wet and humid resistance is poor, so they are not widely used in practical applications. They are especially unsuitable for high-power applications [25].

Nitrogen (oxygen) phosphors have a wide range of excitation spectra, ranging from ultraviolet to green light, excellent luminescence characteristics, high light efficiency and stable thermochemical performance. But the production environment of nitrogen (oxygen) phosphor is demanding and cost is high [26].

Sulfide-based phosphors mainly cooperate with other phosphors to achieve high dominance. The disadvantage of sulfide phosphors is that they have poor wet and thermal stability, are easily decomposed by moisture and produce toxic gases harmful to human body [27].

According to the comparison of the advantages and disadvantages of the above phosphors, YAG phosphors have stable chemical properties and low corrosiveness, so it can not only reduce the impact of many external factors (such as the environment), but also do not cause great harm to human body and is convenient to use. In addition, the accident temperature of YAG phosphor is high, which can reduce the influence of temperature on its performance. Therefore, YAG phosphor is selected to make white light source of semiconductor laser in this paper.

In this paper, the wavelength of the laser is 447 nm, so in order to maximize the optical conversion efficiency of phosphor, we use the YAG-04 yellow phosphor with a wavelength of 440-460 nm. Its emission wavelength is 558 nm, color coordinate x=0.445, y=0.536. Figure 17. shows the physical morphology of YAG-04 yellow phosphor and emission spectra [28].



(a) (b)

Figure 17. YAG-04 phosphor: (a) appearance of YAG-04 phosphor;

(b) emission spectrum of YAG-04 phosphor. [28]

In order to verify that the laser selected in this paper can excite YAG-04 phosphor to synthesize white light, the color coordinates of YAG-04 phosphor can be marked in the chroma diagram of 1931 CIE-XYZ system and investigate its feasibility. Figure 18. is marked as the position of semiconductor laser color coordinates and YAG-04 phosphor coordinates. By connecting the two color coordinates, it can be seen that the straight line passes through the white light region. Therefore, the selected semiconductor laser and YAG-04 phosphor in this experiment can achieve white light. This scheme is feasible.

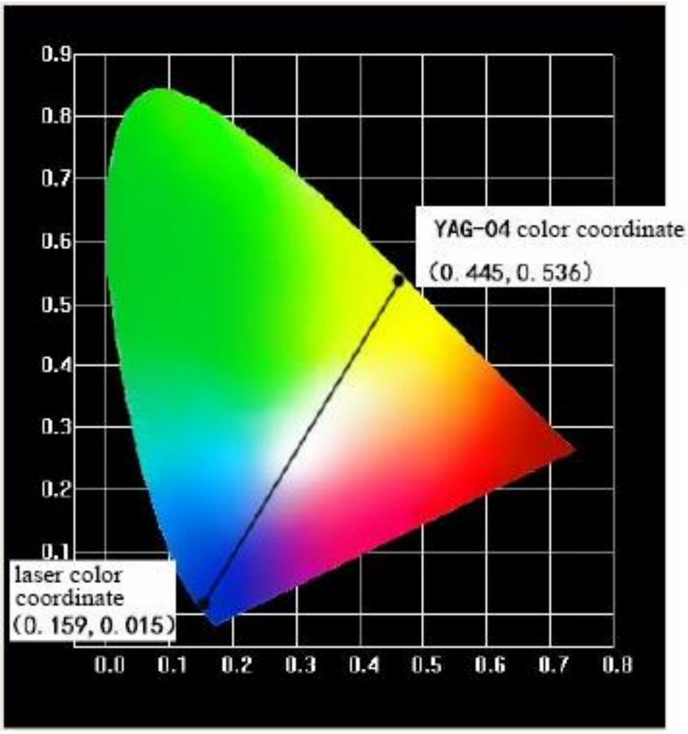


Figure 18. Semiconductor laser color coordinate position and YAG-04 phosphor color coordinate position [54]

4. Photometric properties of white light transformed from laser

In this chapter, we use Tracepro optical software to simulate the light source, and explore the influence of different phosphor parameters on the photometric properties of light source.

Tracepro is an optical-mechanical software developed by Lambda Research in the United States, which conforms to ACIS solid model standard. It can do traditional optical analysis, illumination system design analysis, radiometric and photometric analysis. It is widely used in lens stray light analysis, LED lighting, lamp design and other fields, which is an easy-to-use software. Tracepro is mainly based on non-sequential ray tracing method of Montecarlo principle to analyze the interaction between light and objects. It can not only define and trace millions of light rays, but also deal with complex geometric problems, and also can calculate the absorption, reflection, refraction and diffraction of light in the simulation process. It can calculate and display the real scene very well [29]. TracePro can be used in only five steps:

1) Establishing geometric model;

2) Setting up optical materials;

3) Define light source parameters.

4) Ray tracing;

5) Analysis of simulation results.

4.1 Effect of phosphor concentration on color temperature and color coordinate of light source.

When using Tracepro to simulate phosphor luminescence, the first step is to use the Flourescence Property Generator to establish the absorption spectrum, emission spectrum and the emission spectrum of semiconductor lasers to generate the required phosphor characteristics. In this paper, the stimulation, emission and absorption spectra of YAG-04 yellow phosphor are input, then, the emission spectra of 447 nm blue light semiconductor laser are input, finally the characteristics of YAG-04 phosphor are generated. Figure 18. shows the emission spectra of 447 nm semiconductor lasers simulated in Tracepro.

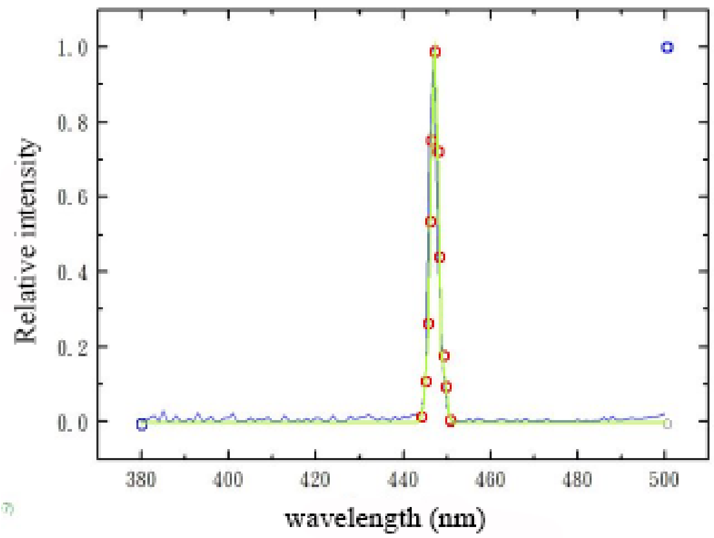
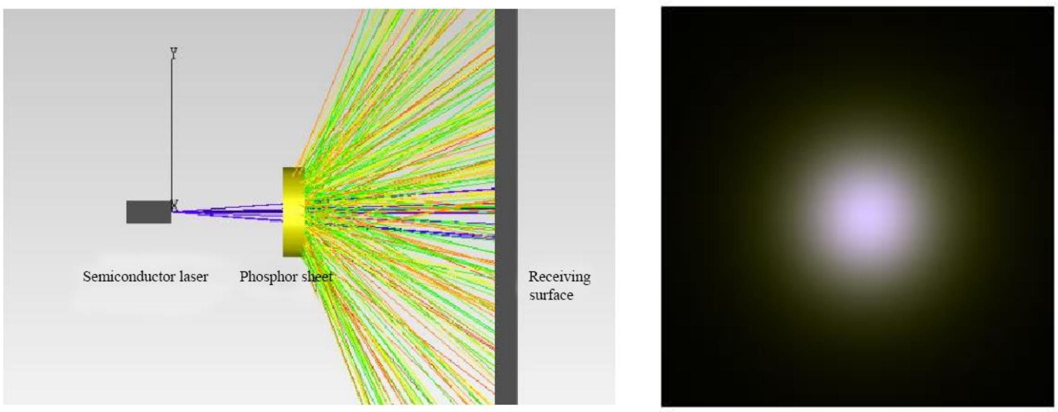


Figure 19. Emission Spectra of Semiconductor Lasers [54]

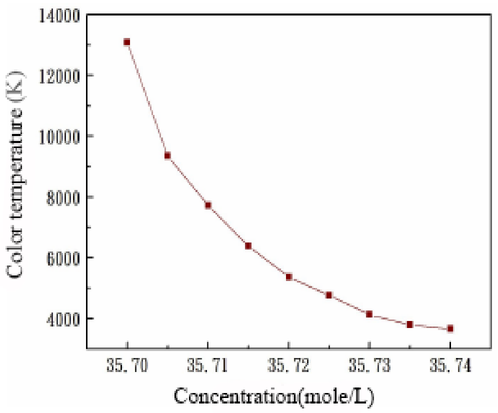
In the process of simulation, the model of phosphor sheet is first established, then the characteristics of YAG-04 phosphor are set, and the quantum efficiency, molar concentration and emission band of phosphor are set. Finally, the fluorescence tracing is added before the light tracing. The excitation model of yellow phosphor sheet excited by semiconductor laser is shown in Figure 20. The phosphor sheet is far away from the luminous surface of the laser, forming a remote phosphor model. A receiving surface is set on the right side of the phosphor sheet to receive the light and color information of the laser white light source. After 10,000 ray tracing simulation, it can be seen that blue light arriving at the receiving surface is mixed with yellow light converted from phosphor to synthesize white light.



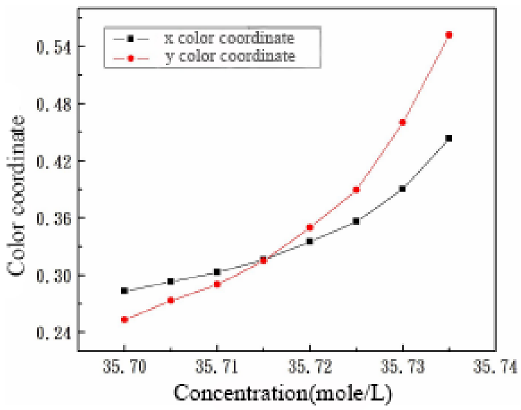
(a) (b)

Figure 20. (a) Luminescence Simulation Structure; (b) White Light Source on Receiving Surface [54]

In order to study the influence of phosphor concentration on light source, the thickness of phosphor sheet was set unchanged, and the change of light source characteristics was investigated by changing the molar concentration of phosphor. Therefore, in the simulation, the thickness of phosphor sheet is set to 1 mm, and the mole concentration of phosphor (moles/liter) is set to 35.700, 35.705, 35.710, 35.715, 35.720, 35.725, 35.730, 35.735, 35.74 respectively. After ray tracing, the relationship curve between the color temperature and color coordinates of the light source center and the concentration of phosphor sheet is obtained, as shown in Figure 21.



(a)



(b)

Figure 21. The influence of phosphor concentration on the light source (a) the relationship between the central color temperature of the light source and the molar concentration of the phosphor; (b) the relationship between the color coordinates of the light source and the molar concentration of the phosphor. [54]

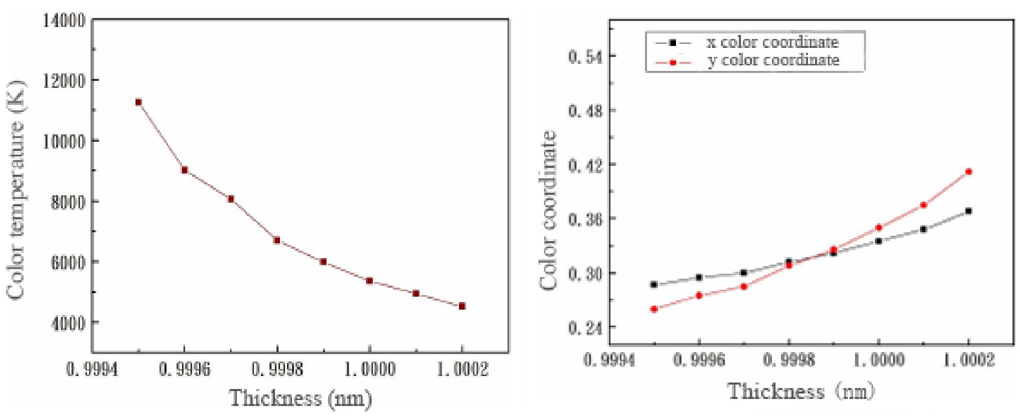
From the relationship curve shown in Figure. 21 (a), we can find that the color temperature of the light source decreases gradually with the increase of the phosphor concentration. Because when the concentration of the phosphor is very small, most of the blue light directly penetrates the phosphor, so the color temperature of the light source is very high. With the increase of the concentration of the phosphor, the distribution density of the phosphor particles in the phosphor increases, which makes more blue light absorbed by the phosphor and transfer into yellow light. The increasing of the yellow light component leads to the decrease of the color temperature.

From this figure, we can also find that when the phosphor concentration increases to a certain extent, the change of light source color temperature become very small and tends to be stable. From this figure, we can also see that when the phosphor concentration increases to a certain extent, the change of light source color temperature is very small and tends to be stable. This is mainly because when the phosphor concentration reaches a certain value, the phosphor particle content in the phosphor sheet is enough, so that the incident blue light is almost absorbed and converted to yellow light, so, even if the phosphor concentration is increased again, the influence on the light source is not so great.

Figure 21. (b) shows the relationship between the color coordinates of the light source and the concentration of phosphor. It can be seen from the graph that the color coordinates of the light source increase with the concentration of phosphor. When the concentration of phosphor increases to 35.73 mole/L, the color coordinates of the light source (x=0.39, y=0.46) have exceeded the white light region [30]. At this time, the light is not white light, but yellow light. This explains the variation of the color temperature of the light source described above with the concentration of phosphor.

4.2 Effect of thickness of phosphor sheet on color temperature and color coordinates of light source.

In order to study the influence of the thickness of phosphor sheet on the light source, the molar concentration of phosphor was set unchanged, and the change of light source characteristics was investigated by changing the thickness of phosphor sheet. In this paper, the molar concentration of phosphor is 35.720 mole/L, and the thickness of phosphor layer (mm) is 0.9995, 0.9996, 0.9997, 0.9998, 0.9999, 1.0000, 1.0001 and 1.0002, respectively. After ray tracing, the relationship between the color temperature and the color coordinates of the light source center and the thickness of the phosphor sheet can be obtained as shown in Figure 22.



(a) (b)

Figure 22. The influence of phosphor thickness on the light source (a) the relationship between the color temperature of the light source and the thickness of the phosphor; (b) the relationship between the color coordinates of the light source and the thickness of the phosphor. [54]

As can be seen from Figure 22, the color temperature of the light source decreases with the increase of the thickness of the phosphor sheet, and the color coordinate of the light source increases with the increase of the thickness. This is mainly because with the increase of the thickness of the phosphor layer, the content of phosphor particles in the phosphor sheet increases. At the same time, the increase of the thickness of the phosphor sheet will also increase the "light trapping effect" of blue light. Thus, blue light will interact with more phosphor particles to stimulate more yellow light when it penetrates the phosphor sheet, resulting in a decrease in color temperature and an increase in color coordinates.

4.3 Chapter summary

Firstly, the function of Tracepro optical simulation software and its basic operation steps are introduced. Based on this, the influence of the concentration and thickness of phosphor sheet on the color temperature and color coordinates of light source is analyzed emphatically. The results show that the increase of the concentration and thickness of phosphor will lead to the decrease of color temperature and the increase of color coordinates of light source. It is worth mentioning that when we use blue light laser with yellow phosphor to excite the white light, because of the deficiency of the red emission, it will result in low color-rendering index and high correlated color temperature. We can add red phosphor to yellow phosphor. The purpose of using red phosphor is to make up for the problem of insufficient color rendering of yellow phosphor, so as to improve the color rendering index of white light source.

5. Principles of transmission of information by laser and white light (Li-Fi)

As we all know, wireless communication technology has undergone tremendous changes in the world since Morse invented telegraph. Traditional wireless communication technology is a kind of communication mode, which makes use of the free propagation of electromagnetic wave signals in space to exchange information. Especially in June 1997, after Institute of Electrical and Electronics Engineers (IEEE) passed 802.11 standard, Wireless Fidelity (WiFi) technology is more and more popular in the world. But the signal of WiFi hotspot is unstable, especially when there are lots of users, the speed of Internet access will much slower. A new technology of Li-Fi visible light communication is coming into researchers' view. The term "Li-Fi" was first proposed by Harald Haas, a professor at the University of Edinburgh in the United Kingdom, at the TED conference in 2011, to implant microchips into LED lights and use the rapid flashing of lights to convey information. Nowadays, Li-Fi's real-time communication rate can reach 50 Gbit/s, equivalent to 0.2s to complete a HD movie download.

Visible light is the perceptible part of the human eye in electromagnetic spectrum. Using LED as a "hot spot" to transmit binary data in wireless communication can not only meet people's needs for illumination, but also solve the unstable problem of WiFi hot spot accessing more users in the near future, which becomes a complementary technology of WiFi. More importantly, visible light communication is harmless to human body and green and healthy because there is no interference of electromagnetic wave.

5.1 Introduction to the working principle of Li-Fi technology.

Li-Fi technology, which is called Light Fidelity, is a wireless communication technology using the transmission medium of visible light source (currently most of them are LED visible lights). By installing a specific micro-control chip in a common LED bulb, the technology can control the LED bulb to turn on and off according to specific rules. When the LED light bulb is on, it is high level "1" and when it is off, it is low level "0". Because of the high-speed characteristics of the control chip, the number of flashes of the LED bulb will reach millions of times per second, so the transmission rate of Li-Fi is very fast. At present, the transmission speed can reach 50Gbit/s under laboratory conditions [31]. On the other hand, the human eye can hardly distinguish the flashing of light after more than 24 flashes per second. Therefore, the human eye can hardly feel the flashing of LED light bulb, which does not affect people's work and rest under normal lighting.

As shown in Figure 23, Li-Fi technology utilizes the LED bulb to transmit information, which is encoded into optical signals (binary coded streams) by the encoder of the LED control chip. Like the WiFi hotspot, as long as the light is illuminated, the light intensity of visible light can be detected according to the receiver. After a series of demodulation processes, optical signals are converted into usable electrical signals for used by receiving devices (mobile phones or laptops), and finally the communication process is completed [31].

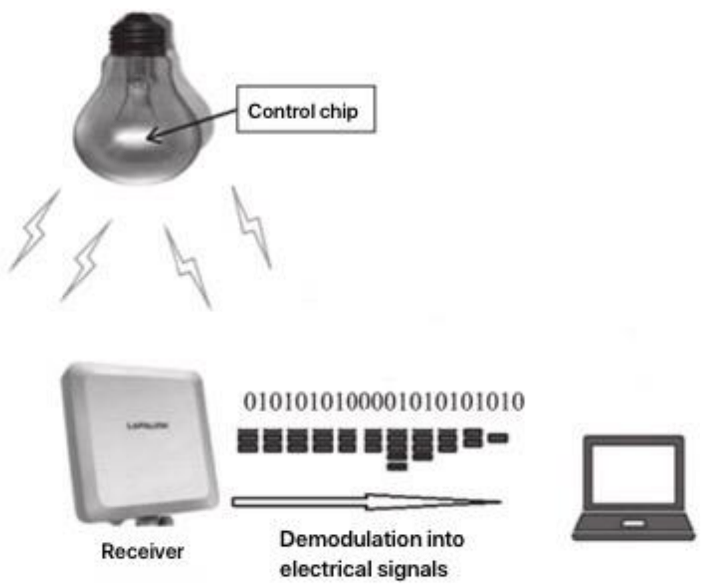


Figure 23. Working principle of Li-Fi: The encoder is encoded into binary ("0", "1") coded stream and sent out. The receiver detects the light and shade changes of the LED light intensity, then demodulates and restores the electrical signal. [31]

5.2 Advantages and Applications of Li-Fi Technology

(1) Li-Fi technology has wide bandwidth and fast transmission rate.

The spectral bandwidth of visible light is 10,000 times that of electromagnetic wave, which is destined to have incomparable advantages of electromagnetic wave. In October 2013, the scientific researchers of Fudan University in China independently developed a high-order modulation and channel equalization algorithm, which made the transmission rate of LED lamp reach the highest 3.25 Gbit/s, and the average internet access rate reach 150 Mbit/s [31].

(2) LED light source is popular, green and healthy.

Nowadays, LED light bulbs have been widely used and bright lights can be seen everywhere. This will mean that Li-Fi wireless communication can be connected to the Internet as long as the LED microcontroller is installed in the place where you want to connect the internet. At the same time, due to the absence of electromagnetic interference in visible light communication, there is no radiation damage to the human body. It is worth mentioning that the controller can be installed on the LED lamp of the aircraft interior illumination to realize the wireless LAN communication in the aircraft interior.

(3) Security of Li-Fi technology.

Because Li-Fi technology uses high-speed LED lights to transmit data, the beam can only travel along a straight line. So it is possible to communicate as long as it is illuminated by LED lights, but it is impossible to communicate where it cannot be illuminated by LED lights. Moreover, the signals of Li-Fi are transmitted independently in the upstream channel and downstream channel using different optical signals. There is no overlap between the optical channels and there will be no mutual interference. This means that if hackers want to invade Li-Fi communication system, they must invade two optical channels at the same time in order to truly complete the invasion. This makes it more difficult for Li-Fi communication system to be invaded and makes the system more secure.

(4) Application of Li-Fi technology.

In the places where there are few base stations and weak wireless communication signals, such as tunnels and expressways, Li-Fi visible light communication is carried out by adding LED controllers to street lamps, so as to meet people's online demand without increasing the number of base stations and affecting daily lighting. It is worth noting that in the near future, when the city is under traffic jams or bad weather, Li-Fi visible light communication between headlights and traffic lights can be used to inquire about road conditions, transmit traffic congestion information, and guide cars to pass on smoother roads and alleviate traffic congestion.

5.3 Comparison of Li-Fi Technology with WiFi Technology

Wi-Fi wireless communication technology has been widely used because it can provide heating points for people to access the Internet. The technology is owned by the Wi-Fi Alliance. It improves the interoperability of wireless network products based on IEEE802.11 standard. Li-Fi technology is similar to WiFi, except that it uses visible light instead of electromagnetic waves. Specifically, as shown in Table 1 [31].

Performance	Li-Fi Technology	WIFI Technology
Transmission speed	50 Gbit/s	54 Mbps in IEEE802.11a standard
Reverse Communication	Not perfectly solved	Mature technology
Link Anti-interference	Easy to interfere with each other	SM Wireless Frequency Interference; Channel Access Collision
Transmission distance	Laboratory conditions are only within 3 M	Transmission distance can meet the daily needs of families
Safety	Higher safety	Easy to invade
Health	No harm to human body	Electromagnetic wave is harmful

Table 1. Comparison between Li-Fi and Wi-Fi

5.4 Problems in Li-Fi Technology

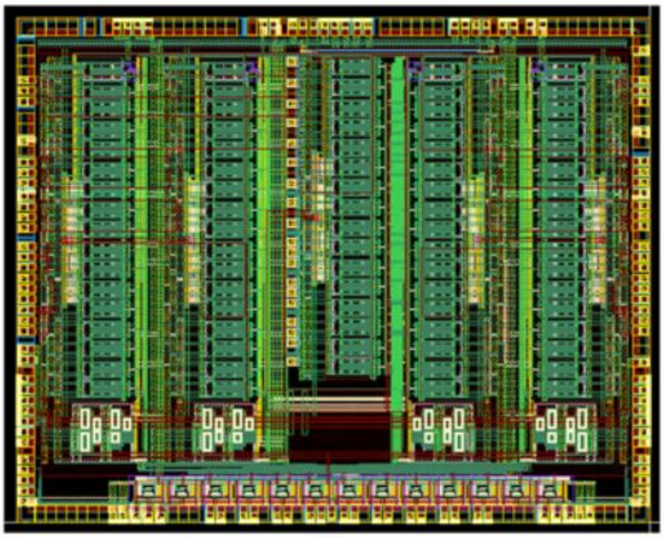
The defects of Li-Fi technology should not be ignored. (1) Because Li-Fi technology uses visible light communication, where light illuminates, it can communicate within 3 meters, but it cannot penetrate obstacles. This is an important reason why WiFi technology will not be replaced by Li-Fi. (2) The LED light bulb emits light signal after the control chip is coded and received by the receiving end, which only completes half of the communication link problem. How to effectively complete the design of the reverse communication link from the receiving end to the transmitting end has become the difficult problem. (3) Environmental interference will also become a difficult problem for Li-Fi technology. For example, the external LED light intensity is stronger, which greatly affects the reliability of the local LED transmission signal [31].

5.5 LiFi components

LiFi technology has wide applications on lighting, car-to-car communication, security and defence, underwater communication and wireless interconnects in data centres. The availability of low-cost and low power miniaturised transceiver technology is regarded as the most important commercial applications of LiFi in daily life such as fifth-generation cellular systems (5G) and the Internet of Things (IOT).

5.5.1 Transmitter Chip

Conventional circuits that support orthogonal frequency division multiplexing (OFDM) or pulse amplitude modulation (PAM) involve a digital-to-analogue converter (DAC) to generate high-speed signals. Typical DAC structures can only deliver up to 30 mA current [32], and they require an additional stage of current amplifier in order to drive a typical LED. An open-drain 8-bit current steering DAC-based LED driver using Complementary Metal Oxide Semiconductor (CMOS) technology has been developed in [33], and it omits the additional current amplifier. The layout and package of the chip are shown in Figure 24(a) and (b), respectively. The ASIC is capable of achieving 250 MS/s at a maximum full-scale current of 255 mA and exhibits a power efficiency of 72%. A differential optical drive is implemented by employing both current steering branches of the DAC to drive two different color LEDs. This doubles the signal level and efficiency over a single ended approach, and enables the transmitter configuration described in [34]. The chip has four separate driver channels. Each channel can drive up to two LEDs, allowing Color shift keying (CSK), illumination color temperature regulation and multiple input multiple output (MIMO) systems.



(a)

(b)

Figure 24. [34] LiFi transmitter chip – developed within UPVLC project. (a) Layout of LiFi driver chip in CMOS. (b) Packaged LiFi driver chip (size:3.3 × 3.3 cm^2 — the actual silicon die is 5 mm × 6 mm), with a coin alongside to give the scale.

An analysis of the bit error rate (BER) as a function of measured signal to-noise ratio

(SNR) at different full-scale currents is shown in Figure 25. An uncoded OFDM signal is used in the experiment. The distance between the LED and the receiver is 1 m. As expected, an increase in the full-scale current results in a higher optical output power and, hence, higher SNR at the receiver. The system is subject to non-linear distortions at the transmitter and the receiver. Therefore, an SNR of about 25 dB is required to achieve an uncoded BER of 10^{-3}. As shown in Figure 25, the BER does not improve when the current reaches about 250 mA due to saturation effects. It has been shown that it is possible to transmit 1 Gb/s when using all four drivers in parallel in a MIMO configuration [35].

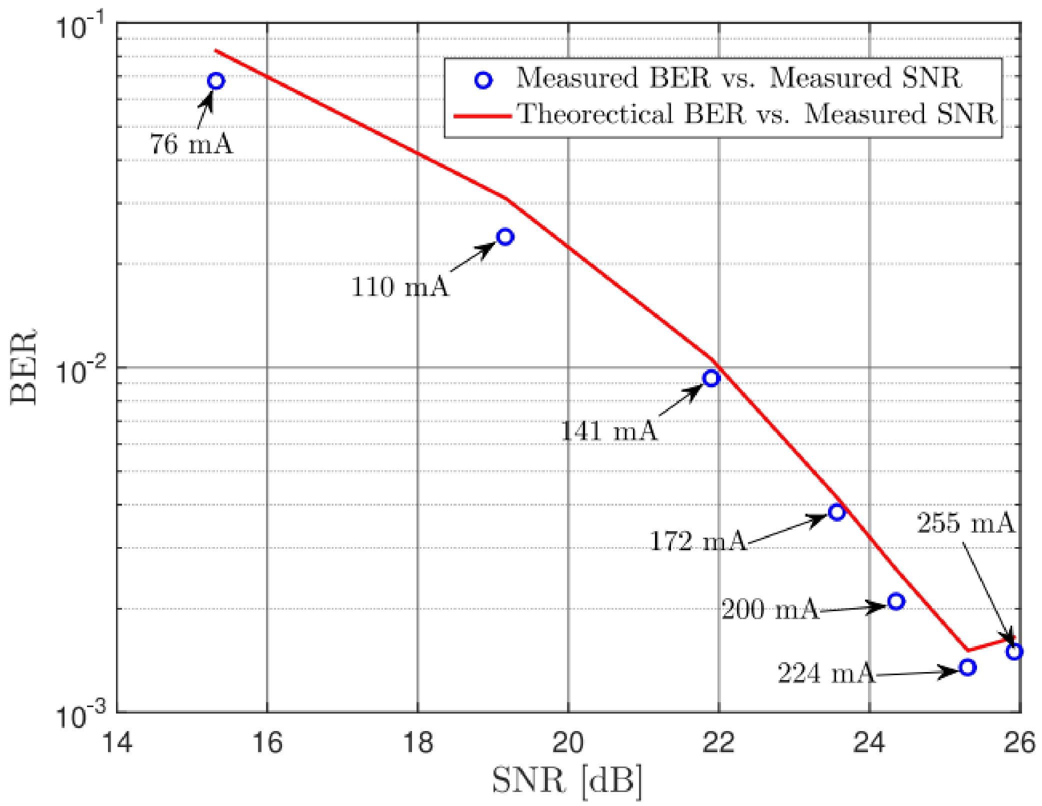
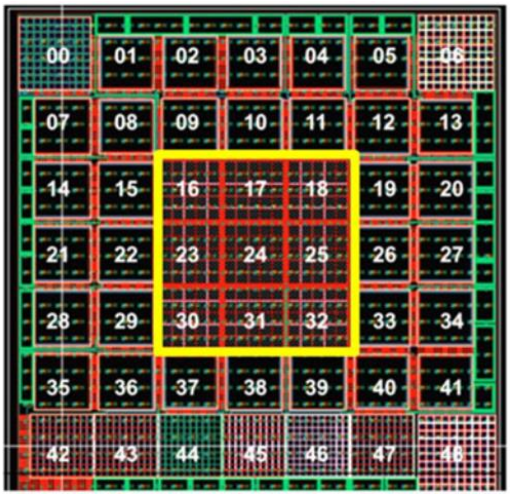


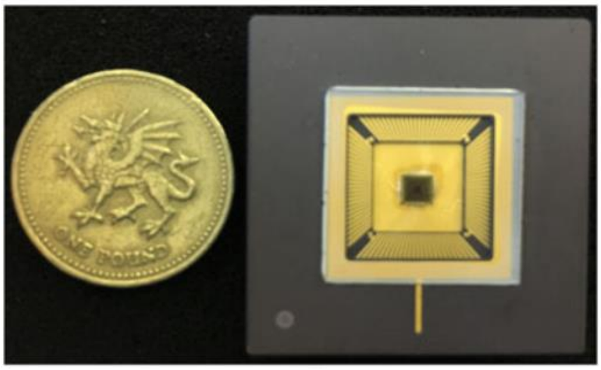
Figure 25. [35] BER of the DAC in the CMOS transmitter chip.

5.5.2 Receiver Chip

LiFi systems are based on intensity modulation-direct detection (IM/DD). As a consequence, the average transmit power is proportional to the transmit signal amplitude, and not the square of the signal amplitude. The electrical path loss is hence twice the optical path loss. Therefore, in order to achieve reasonable distances in an attocell network, receiver devices with sufficiently high sensitivity are required. Based on computer modelling, it is indicated in [35] that an avalanche photodetector (APD)-based receiver with a typical input referred noise density of 10 pA/$\sqrt{\text{Hz}}$ is necessary for reliable communication. A LiFi receiver chip composed of 49 APD detectors (a 7 × 7 detector array) based on 180 µm CMOS technology has been developed (see Figure 26.). The size of each APD element is 200 µm × 200 µm placed on a 240 µm grid. The responsivity of the nine APDs at the central core is 2.61 A/W at 450 nm. An APD gain of 10 dB is achieved at a reverse bias voltage of only 10 V. Each APD is connected to an integrated transimpedance amplifier based on a shunt-shunt feedback topology with fixed gain in order to obtain good performance. The APDs achieve a bandwidth of 90 MHz. The APDs outside the central core exhibit different color sensitivities. Also, there are several APDs at the fringe (numbers 6, 8 and 42–48) that are exposed to a specially designed metal grading structure to achieve enhanced directionality for angular diversity receiver algorithms [36].



(a)



(b)

Figure 26. [36] LiFi receiver chip – developed within Unplasticized Polyvinyl Chloride (UPVLC) project. (a) Layout of LiFi receiver chip with 49 APD detectors on CMOS.

(b) Packaged LiFi Receiver chip (size: 3.3 × 3.3 cm2 — the actual silicon die is

3 mm × 3 mm), with a coin alongside to give the scale.

5.6 Modulation technique for LiFi

In this section, general applications of digital modulation techniques on LiFi are summarized. In addition, some special issues and requirements are discussed. In principle, LiFi also relies on electromagnetic radiation for information transmission.
Thus, combined with necessary modifications, it is possible that typically used modulation techniques in radio frequency (RF) communication can be utilized to LiFi. Moreover, LiFi can provide a number of unique and specific modulation formats, since visible light is used on wireless communication.

5.6.1 Single-Carrier Modulation (SCM)

Widely used SCM schemes for LiFi include on-off keying (OOK), pulse position modulation (PPM) and pulse amplitude modulation (PAM), which have been studied in wireless infrared communication systems [37]. OOK is one of the well known and simple modulation schemes, and it provides a good trade-off between system performance and implementation complexity. By its very nature that OOK transmits data by sequentially turning on and off the LED, it can inherently provide dimming support. As specified in IEEE 802.15.7 [38], OOK dimming can be achieved by: i) refining the ON/OFF levels; and ii) applying symbol compensation. Dimming through refining the ON/OFF levels of the LED can maintain the same data rate, however, the reliable communication range would decrease at low dimming levels. On the other hand, dimming by symbol compensation can be achieved by inserting additional ON/OFF pulses, whose duration is determined by the desired dimming level. As the maximum data rate is achieved with a 50% dimming level assuming equal number of 1 and 0 s on average, increasing or decreasing the luminance of the LED would cause the data rate to decrease [39].

Compared with OOK, PPM is more power-efficient but has a lower spectral efficiency. A variant of PPM, termed variable pulse position modulation (VPPM) [38], can provide dimming support by changing the width of signal pulses, according to a specified luminance level. Therefore, VPPM can be viewed as a combination of PPM and pulse width modulation (PWM). A novel SCM scheme, termed optical spatial modulation [40], which relies on the principle of spatial modulation, proves to be both power- and bandwidth-efficient for indoor optical wireless communication. As a variant of quadrature amplitude modulation (QAM) for single carrier systems, carrier-less amplitude and phase modulation uses two orthogonal signals, in place of the real and imaginary parts of the QAM signaling format, for spectrum-efficient signal transmission in LiFi networks [41].

5.6.2 Multi-Carrier Modulation

As the required data rate increases in LiFi networks, SCM schemes such as OOK, PPM and PAM start to suffer from unwanted effects, such as non-linear signal distortion at the LED front-end and inter-symbol interference caused by the frequency selectivity in dispersive optical wireless channels. Therefore, for high-speed optical wireless communication, efforts are drawn to multi-carrier modulation (MCM). Compared with SCM, MCM is more bandwidth-efficient but less energy-efficient. One and perhaps the most common realisation of MCM in LiFi networks is OFDM, where parallel data streams are transmitted simultaneously through a collection of orthogonal subcarriers and complex equalization can be omitted [42], [43]. If the number of orthogonal subcarriers is chosen so that the bandwidth of the modulated signal is smaller than the coherence bandwidth of the optical channel, each sub-channel can be considered as a flat fading channel. Techniques already developed for flat fading channels can therefore be applied. The use of OFDM allows for further adaptive bit and power loading techniques on each subcarrier so that enhanced system performance can be achieved. An OFDM modulator can be implemented by an inverse discrete Fourier transform block, which can be efficiently realized using the inverse fast Fourier transform (IFFT), followed by a DAC. As a result, the OFDM generated signal is complex and bipolar by nature. In order to fit the IM/DD requirement imposed by commercially available LEDs, necessary modifications to the conventional OFDM techniques are required for LiFi [39].

The commonly used method for ensuring a real-valued signal output after IFFT is by enforcing Hermitian symmetry on the subcarriers. Moreover, as the light intensity cannot be negative, the LiFi signal needs to be unipolar. There are many methods to obtain a unipolar time-domain signal. DCO-OFDM [37] uses a positive direct current (DC) bias for unipolar signal generation. This method brings an increase in the total electrical power consumption, but without further loss in spectral efficiency. Asymmetrically clipped optical OFDM (ACO-OFDM) [44] is another type of optical OFDM scheme where, as well as imposing Hermitian symmetry, only the odd subcarriers are used for data transmission and the even subcarriers are set to zero. Therefore, the spectral efficiency of ACO-OFDM is further halved. Since only a small DC bias is required in ACO-OFDM, it is more energy-efficient than DCO-OFDM. Asymmetrically clipped direct current biased OFDM (ADO-OFDM) [45] is a combination of DCO-OFDM and ACO-OFDM, where the DCO-OFDM scheme is used on the even subcarriers and the ACO-OFDM scheme is used on the odd subcarriers. In certain scenarios, it is shown that ADO-OFDM outperforms both DCO-OFDM and ACO-OFDM in terms of power-efficiency. To incorporate dimming support into optical OFDM, reverse polarity optical OFDM (RPO-OFDM) [46] was proposed to combine the high rate OFDM signal with the slow rate PWM signal, both of which contribute to the overall illumination of the LED. Since RPO-OFDM fully utilizes the linear dynamic range of the LED, non-linear signal distortion is minimised. Another modulation scheme, termed PAM discrete multitone modulation [47], also clips the entire negative signal as in ACO-OFDM. The difference is that pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) uses all of the available subcarriers for information transmission, however, only the imaginary parts of the signal are modulated on each subcarrier. In this way, signal distortion caused by asymmetric clipping falls on the real component, and is orthogonal to the information-carrying signal. A hybrid optical OFDM scheme combining ACO-OFDM and PAM-DMT, termed asymmetrically hybrid optical OFDM (AHO-OFDM) [48], uses both odd and even subcarriers for information transmission. In AHO-OFDM, dimming capability is supported by a DC bias without a further requirement of the commonly used PWM technique. The fact that compact multi-LED arrays can be realised straightforwardly has led to a new OFDM technique that assigns subcarriers to physically separated LEDs in an array [49]. This helps mitigate non-linear distortions due to high peak-to-average power ratio in OFDM.

As an alternative to ACO-OFDM, flip-OFDM [50] and unipolar OFDM (U-OFDM) [51] can achieve comparable bit error ratio (BER) performance and spectral efficiency. A novel modulation scheme, named enhanced unipolar OFDM (eUOFDM) [52], allows a unipolar signal generation without additional spectral efficiency loss as in ACO-OFDM, PAM-DMT, flip-OFDM and U-OFDM. Recently, an alternative to OFDM has been proposed [53], which uses the Hadamard matrix instead of the Fourier matrix as an orthogonal matrix to multiplex multiple data streams.

5.6.3 LiFi Specific Modulation

LiFi transmitters are generally designed not only for wireless communication but also for illumination, which can be realized either by using blue LEDs with yellow phosphorus coating or by color mixing through colored LEDs. Luminaires equipped with multicolored LEDs can provide further possibilities for signal modulation and detection in LiFi systems [55].

CSK is an IM scheme outlined in IEEE 802.15.7 [38], where signals are encoded into color intensities emitted by RGB LEDs. In CSK, incoming bits are mapped on to the instantaneous chromaticities of the colored LEDs while maintaining a constant average perceived color. The advantages of CSK over conventional IM schemes are twofold. Firstly, since a constant luminous flux is guaranteed, there would be no flicker effect over all frequencies. Secondly, the constant luminous flux implies a nearly constant LED driving current, which reduces the possible inrush current at signal modulation, and thus improves LED reliability. Based on CSK, metameric modulation (MM) [56] was developed and it can achieve higher energy efficiency and provide further control of the color quality, however, with the disadvantage of requiring an additional and independently controlled green LED. From the perspective of maximising the communication capacity, color intensity modulation (CIM) is proposed in [57]. For both orthogonal and non-orthogonal optical channels.

6. Conclusion

During the research period of this paper, by consulting a large number of data, the development status of white light source of semiconductor lasers is summarized, and the realization method of white light source of semiconductor lasers is analyzed. The following conclusions are drawn:

1. Semiconductor laser white light source usually has three realization forms: multi-color laser mixing, near-ultraviolet laser exciting RGB tricolor phosphor and blue laser exciting yellow phosphor to synthesize white light. Among them, blue light excitation of yellow phosphor is the most promising way to industrialize, although its color rendering is not high, but it can meet the lighting needs, and has the advantages of small size, high luminance, long working cycle and stable light color. This paper theoretically validates the feasibility of white light synthesis from YAG-04 phosphor excited by 447 nm blue laser diode.
2. The concentration and thickness of phosphor have a certain influence on the color temperature and color rendering index of white light source.When the thickness of phosphor is fixed, the color temperature and color rendering index of light source will decrease with the increase of phosphor layer concentration. However, when the phosphor concentration increases to a certain extent, with the further increase of the phosphor concentration, the range of color temperature reduction of the light source decreases a lot. When the phosphor concentration is constant, the color temperature and color rendering index of the light source will increase with the decrease of the thickness of the phosphor sheet.
3. Comparing with WiFi technology, the advantages and disadvantages of LiFi communication technology are discussed. Moreover, the LiFi component, digital modulation techniques generally used for LiFi are summarised, and some special issues and requirements are discussed.

With the development of the times, it has become a trend to develop more efficient and high-power solid-state lighting sources. The light source based on white light of semiconductor laser has many advantages, such as small size, low energy consumption, stable light color and long working life. It is a new generation of solid-state lighting source with good development prospects. Meanwhile, with the development of LiFi technology, it will provide great convenience for people's daily life in the future.

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