Investigation on characteristic of LED power density via tapered fiber

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Abstract

In this paper, a tapered fiber for improving the power density of the Light Emitting Diode (LED) was designed. Numerical simulation showed that the tapered fiber makes the LED diverging light sources converge on the microscopic area, which makes the LED available for biomedical photonic imaging in the microenvironment. Based on the Monte Carlo Ray Tracing Method, we obtained the law of spot illumination and divergence angle when the light passes through the different parameters tapered fiber. In addition, the tapered fiber was designed as a spiral shape with steadily changing slope, and the effect of the spiral-bending coefficient on the light-gathering properties of the fiber was studied. The concentrating performance of tapered fiber is related to the length, size, and spiral-bending coefficient. The tapered fiber can effectively reduce the illuminant area and improve the power density of the light source.

1. Introduction

Light Emitting Diode (LED), also known as a solid light source, recently has attracted broad interest in the lighting research field [1–6]. LED is used in various types of lighting places because of low operating voltage, microstructural, low cost, low radiation, and other features. The application technology of LED light sources gained widespread popularity [7, 8]. A lot of progress has been made in improving the power of LED. In the visible range, high brightness LED has become a standard light source for various application such as household lighting, automobile industry etc. The output power has surpassed incidence bulb and fluorescent bulb by a large margin. The main limitation at the moment is the internal quantum efficiency and the light extraction efficiency.

To improve the LED’s performance, several methods have been proposed, such as epitaxial lateral overgrowth, surface roughening [9, 10], the metal mirror reflects layer [11], photonic crystal structures [12, 13], and patterned sapphire substrate. However, these methods are rarely used in commercial applications due to their high cost and low throughput [14]. The single LED chip is regarded as the lambert source with the large divergence angle [15], therefore it cannot be used as an aggregation light source alone. High illumination light source can be obtained by combining multiple LED chips and concentrating the light through lenses or other light concentrating substances. This way has many problems with heat dissipation, large volume and poor effect, which makes the development of LED sources become progressively difficult in a microenvironment [16–18].

For the common optical fiber, when the fiber is drawn into a sudden cone, the fiber diameter decreases rapidly, resulting in the light escape from the side wall of the optical fiber [19, 20]. However, the tapered fiber can concentrate light on a small surface and then improve the luminous flux per unit area. The spiral-bending tapered fiber is the tapered optical fiber drawn in a spiral distribution, which exhibits a magical property.

In this paper, we investigated systemically the LED optical power density via tapered fiber. By adjusting the structure parameters of tapered fiber, the LED diverging light source can converge on the microscopic area. Meanwhile, we obtained the transmission characteristics when the light passed through tapered spiral bending fiber. The simulation results showed that the length, the size, and the spiral-bending coefficient of fiber have powerful enhancement concentration effect. Because the tapered fiber has the characteristics of light gathering,
the combination of tapered fiber and LED light source makes the LED be applied in biomedical photonic imaging in a microenvironment. This method can effectively reduce the structure of the concentrating equipment and improve the optical power density of the light source per plant. In addition, the spiral-bending tapered fiber shows peculiar light gathering characteristics, which further expands the application direction of LED chip source.

2. Structure design

Figure 1 shows that the structure principle diagram for improving the LED optical power density. The overall auxiliary structure is composed of three parts, which consist of an LED chip, the tapered fiber with specific structure parameters and two rectangular detectors. In the simulation, the LED chip light source (Philips LUXEON White LED) is used as the light source, whose footprint is set to 1.0 mm × 1.0 mm and the energy is 1 lumen. Since the LED light source is a mixed light source, the wavelengths of 507 nm, 539 nm, 579 nm, 622 nm, and 656 nm are used to numerically simulate the LED white light source according to the ratio of

\[
0.072:0.146:0.198:0.230:0.222:0.230:0.132.
\]

The number of light source tracing rays is 5 M, the maximum number of intersections of rays per day is 4000, and the maximum number of fragments is 5000. The material of tapered fiber core is K5 glass and the substrate material of cladding is FK3 glass. Their structure materials with the refractive index are 1.5225 and 1.4645 at wavelength of 585 nm. The core radius and cladding radius ratio are 2:5, and the ratio does not change with the length. The LED chip locates at the horizontal center of the large end, and the distance between them is set as 0.1 mm. Two rectangular detectors are located at the small end, their function is to collect the light coming out of the small end. By exploring the energy distribution of the light on the rectangular detector and the change of the spot size, the optimal condensing parameters of the tapered fiber are obtained.

Figure 2 shows the transmission properties of light in the tapered fiber from the large end to the small end. The incident angle of light (\(\alpha_n\)) and the corresponding transmission mode of characteristic angle (\(\theta_n\)) can be obtained according to the geometric relationship and law of refraction in the figure. Tapered fibers are step-index fibers, when the light through into the tapered fiber, the incident angle of light gradually decreases with the reflection times. Meanwhile, the characteristic angle of the transmission mode increases with the augment of reflection times:

\[
\alpha_n = \pi \quad \frac{n_0}{n_1} \sin^{-1} \alpha - (2n - 1) \frac{\delta}{2}
\]

\[
\theta_n = \frac{n_0}{n_1} \sin^{-1} + n\delta
\]

where \(\delta\) is the taper angle of fiber and \(n\) shows the times of light reflections. Moreover, \(n_0\) and \(n_1\) are the refractive index of core and cladding, respectively. According to the formula, when the light transmits from the large end to small end, the incident angle of light (\(\alpha_n\)) in the tapered fiber always decreases. Therefore, the total reflection condition will break down and the light in the core can be seriously divulged. In order to ensure that the incident light can be smoothly emitted from the small end, the tapered fiber should be satisfied:
\[ \sin \left( \frac{\theta_0 + \delta}{2} \right) \leq \frac{r_1}{r_2} \left[ 1 - \left( \frac{n_3}{n_1} \right)^2 \right]^{1/2} \]  

(3)

Where \( r_1 \) and \( r_2 \) are the radius of the small end and the large end of the tapered fiber respectively. When \( \cos \left( \frac{\delta}{2} \right) \approx 1 \), we can know from the above formula:

\[ \sin \left( \frac{\delta}{2} \right) \leq \frac{r_1}{r_2} \left[ 1 - \left( \frac{n_3}{n_1} \right)^2 \right]^{1/2} - \sin \theta \]  

(4)

In the formula, \( \sin \frac{\delta}{2} = \frac{r_3 - r_1}{l_0} \), \( l_0 \) is the length of the fiber. In order to ensure the tapered fiber can concentrate light, the fiber should have a minimum length of \( l_0 \). But LED chip is the lambert source, we can only obtain the optimal length.

\[ l_0 \geq \frac{r_2 (r_2 - r_1) \cos \theta}{n_1 \left[ 1 - \left( \frac{n_2}{n_1} \right)^2 \right]^{1/2} - r_2 \sin \theta} \]  

(5)

Because the core radius and cladding radius ratio are 2:5, the LED divergent light primordially enter more into the cladding, and core light possibly leaks as the fiber length grows. We need to consider the transmission properties of light at the tapered fiber cladding. Figure 3 shows the proportion of light in the core of fibers of different lengths as a function of the large end cladding radius \( r_3 \). The light mainly transmits in the tapered fiber cladding, meanwhile, the amount of light transmitted in the core decreases with the increase of the fiber length, and increasing \( r_3 \) can effectively increase the proportion of transmitted light in the core. When the light travels through the cladding, the light also leaks out at the contact surface between cladding and environment with the change of optical transmission distance and fiber taper. As the fiber length is short, the state of cladding light
transmission is not negligible. The energy of the LED light source mentioned in this article is 1 lumen, and there is a linear relationship between the energy of the incident end of the fiber and the radius of the large end of the fiber. When the large end cladding radius is 62.5 μm, the light energy received by the incident end of the fiber is 0.73 lumen; When the radius of the large port of the fiber is 25 μm, the energy of the incident end of the fiber is 0.017 lumen.

In this paper, the simulation software based on the Monte Carlo Ray Tracing Method is used to simulate the LED white light transmission characteristics of light in tapered fiber are simulated and a method for improving LED light power density in the microenvironment is presented. It is worth mentioning that the tapered fiber cannot increase the total luminous flux of LED, but it increases the luminous flux per unit area on the small face and improves the optical power density.

3. Numerical analysis

In the simulation calculation process, we calculate the spot luminous flux and divergence angle according to the spot size and the distance between the two rectangular detectors. In this paper, the small end size of the tapered fiber is fixed, whose core radius \( r_1 = 25 \mu m \) and the cladding radius \( r_4 = 62.5 \mu m \). And \( r_2 \) is the large end core radius, which is the scalar multiple of \( r_1 \). Similarly, \( r_3 \) is the radius of the fiber cladding large end. Because the ratio does not change with the length, so \( r_3 \) is used to represent the size of the fiber large end face. Figure 4 shows the variation of spot luminous flux with the large end cladding radius \( r_3 \) under different fiber lengths. The luminous flux decreases as the length when the large end cladding radius \( r_3 \) is fixed. For the short fiber \( l \leq 50 \text{ mm} \), expanding \( r_3 \) is capable of an increase in the proportion of light transmission in the core, and decreasing the length is able to increase the transmission amount of light in core. Therefore, the luminous flux value shows an increasing trend with the change of \( r_3 \). When \( l \) is greater or equal to 75 mm, the luminous flux first increases and then decreases with the expansion of \( r_3 \). The proportion of light transmission in the core decreases with increasing length, which results in an abnormal variation of luminous flux value. And the length variation of the tapered fiber plays a decisive role in short distances.

The smaller the spot divergence angle is, the stronger the convergence capability of the conical fiber is. Figure 5 shows the spot divergence angle change between the length \( l \) and the large end cladding radius \( r_3 \) under different fiber lengths. When \( l < 50 \text{ mm} \), the divergence angle increases with the increase of \( r_3 \). In the case where \( l \) is equal to 50 mm, the divergence angle decreases first and then increases. The curious change can be related to the luminous flux at the \( l \leq 50 \text{ mm} \), the reason is that the light travels mainly over short distances through the tapered fiber core, and the proportion becomes more obvious with the increase of \( r_3 \). However, the light in the core leaks out into the cladding, which leads to the increase of the light spot area, and then results in the abnormal change of the light spot divergence angle. The spot divergence angle increases correspondingly when \( l \) goes from 75 mm to 400 mm. In this paper, improving the optical power density is of primary importance. As shown in figure 6(a), the variation of spot illumination with the large end cladding radius \( r_3 \). The illumination decreases as the length when the large end cladding radius \( r_3 \) is fixed. In the case of \( l = 75 \text{ mm} \),
the illumination values basically do not change with \( r_3 \). When \( l \) is greater than 75 mm, the spot illumination first increases and then decreases. The peculiar change is closely related to the luminous flux and spot size. The optical power density and the actual length are taken into account, the length \( l = 75 \) mm is auto fitted. Figure 6(b) shows the changes of spot illumination and divergence angle at \( l = 75 \) mm. The trend of illumination values firstly increase and then decrease, the divergence angle reduces all the time as the \( r_3 \) expands overall, so the fiber specifications in this state are identified as critical thresholds. When \( l = 75 \) mm, \( r_2 = 0.2 \) mm, \( r_3 = 0.5 \) mm, and the input power at the entrance of the fiber is 0.63 lumen, the best illumination is 0.9925 lm mm\(^{-2}\) and the divergence angle is 62.76 degrees.

In an optical fiber lighting system, bending loss is an important factor affecting lighting quality. The bending loss of traditional fiber is caused by deformation during bending, the operating principle is similar to that of tapered fiber, which changes the symmetrical geometrical structure of fiber and the incident angle of light \((\alpha_i)\) [26]. The spiral-bending tapered fiber loss is related to taper and degree of the crook, especially when the fiber is bent less than the critical radius, the losses will increase rapidly [27]. The bending loss characteristics of tapered fibers are considered when the bending radius is smaller than the minimum allowable bending radius, and the critical radius of optical fibers is expressed as:

\[
R_{\text{min}} = \frac{R}{\Delta^2}
\]

where \( R \) is the core radius of the fiber, and \( \Delta \) is the relative refractive index difference. In this paper, \( \Delta \) is equal to 0.037, but \( R \) is uncertain due to the fiber being tapered. So \( R_{\text{min}} \) is between 10 mm and 60 mm. According to

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**Figure 5.** The changes of spot divergence angle with the large end cladding radius \( (r_3) \) under different fiber lengths.

**Figure 6.** (a) Diagram of spot illumination with the large end cladding radius \( (r_3) \) under different fiber lengths. (b) The changes of spot illumination and divergence angle with \( r_3 \) at \( l = 75 \) mm.
the helix length \( (L_s) \) formula:

\[
L_s = N_s \sqrt{[(\pi S)^2 + S^2]}
\]  

where \( N_s \) is the number of bending turns of the optical fiber, \( S \) is the fiber screw pitch and \( D \) is the fiber bending diameter. The schematic diagram of spiral-bending tapered fiber is shown in figure 7. The \( S \) is 2 mm and its value is fixed, the length of fiber is changed by debugging the values of \( D \) and \( N_s \) in the following research. In order to investigate the bending loss characteristics, the minimum value of \( R_{\text{min}} \) is 10 mm, so two structure parameters were selected for simulation when the \( D = 20 \) mm and \( D = 30 \) mm.

The increase of \( r_3 \) will improve the ability of receiving light for optical fiber, but the fiber taper could cause a leak of light. As shown in figures 8(a) and (b), the variation of transformation laws of luminous flux with increasing \( r_3 \) when the bending diameter of optical fiber \( D = 20 \) mm and \( D = 30 \) mm, respectively. When the turn number \( (N) \) keeps constant, the luminous flux fluctuates as \( r_3 \) increases. And changing turn number can affect the luminous flux value, but which has little influence on the overall change law when the turn number \( N \geq 5 \). At \( D = 20 \) mm, the divergence angle line chart is shown in figure 8(c). With the large cladding radius \( (r_3) \) remains constant, the more turn number \( (N) \) and the smaller the spot divergence angle, the pattern of change remaining roughly the same yet. Figure 8(d) shows the variation of divergence angle at \( D = 30 \) mm, the maximum divergence angle increases somewhat, but when the number of turns is greater than 5, the result is
equivalent to that at 20 mm. Due to an increase of the bending length will consume the transmitted light of the cladding, when the bending length reaches a threshold, the light is transmitted mainly in the fiber core, thus reducing the light spot divergence angle. According to the equation (7), the number of \( N \) directly affects the length of the spiral-bending tapered fiber. When the number of \( N \) is greater or equal to 5, the change in luminous flux and divergence angle is similar. The spiral-bending tapered fiber is characterized by light propagating mainly in the core but leaking in the cladding.

By optimizing the spot size, we obtained the variation rule of optical power density. Figures 9(a) and (b) show the variation of spot illumination with the \( r_3 \) and the turn number (\( N \)) when the \( D = 20 \) mm and \( D = 30 \) mm respectively. The result shows the concentrating effect of spiral-bending tapered fiber becomes more significant than the expansion of \( r_3 \). And the turn number (\( N \)) enables to affect the optimal value of concentrating effect, but the transformation law does not change. By comparing the results of \( N = 3 \), and other parameters, we can infer that the tapered spiral bending has the optimal thresholds of length. When the length reaches the threshold and \( r_3 \) is certain, the spot illumination value decreases with the increase of fiber length. Figure 10 shows the spot energy distribution on the end face of the spiral-bending tapered fiber. Figures 10(a) and (b) respectively show the variation of spot power density distribution when \( D \) is equal to 20 mm, \( r_3 = 62.5 \) \( \mu \)m and \( r_3 = 0.5 \) mm. The figure is detailed enough to see gathering to the light core. However, the phenomenon with the cladding guiding light is inevitable due to the structure characteristics of conical fiber itself. Simulation results show that the spiral-bending tapered fiber can focus the LED light on a small area and improve the optical power density. Meanwhile, the size of the tapered fiber end is similar to the ordinary optical fiber and the light is focused on the core. Therefore, the combination of LED and the tapered fiber can effectively expand the application prospect of the LED light sources.
4. Conclusion

In this paper, the characteristic of the light transmission through the tapered fiber from the Light Emitting Diode (LED) was obtained. Based on the Monte Carlo Ray Tracing Method, the changes of spot luminous flux and spot divergence angle under different tapered fiber structural parameters were compared. All phenomena indicated that the tapered fiber can make the light emitting from the LED chips converge on the microscopic scale and improve the optical power density of LED, which makes the LED chip a high illumination light source of the microenvironment. It should be especially stated that the spiral-bending tapered fiber can effectively focus the light on the core and dissipate the cladding light, thus improving the optical power density. In addition, the size of tapered fiber small end is the same as the ordinary optical fiber, so the combination of the LED light source and tapered fiber further expands the application prospect of the LED light source. The structure effectively enables LED applications in the biomedical photonic imaging, and plays an important role in miniaturizing LED.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Disclosures

The authors declare no conflicts of interest.

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