Numerical Investigations on a Distributed Fiber-Optic Lighting System with an End Reflector

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Abstract A novel distributed fiber-optic decorative lighting system with the reflection coating on the extremity of fiber-optic is designed, which used the multi-mold optical fibre made up of large core diameter (Diameter of core and cladding is 105μm and 125μm, respectively). After introducing the distributional optical fiber decorative lighting system briefly, the relationship between corrosion depth of the optical fiber core and the leakage of fiber-optic has been analyzed with the Rsoft, and then the relationship of the lighting power and the uniformity of lighting power with the leakage rate of optical fiber lamp, the reflective of reflection coating has been discussed. The simulation analysis shows that, when the core diameter is corroded to 80~85 μm, the leakage rate of optical fiber may achieve 5.0%, which suits the optical fiber decorative lighting. Considering all kinds of factors, when optical fiber lamp's quantity is 20, the coating index of reflection is 95%, optical fiber lamp's leakage of light rate is 5.0%, and the optical fiber lamp's distance is 1 meter, the quite high illuminating power may be achieved, as well as the good lighting uniformity. Finally the experimental study of decorative lighting system is given. And the experimental result is in keeping well with the theory simulation conclusion.

Keywords Fiber-Optic Lighting, Reflector, Numerical Simulation

1. Introduction
Fiber-optic lighting has been developed for 30 years in 20th century. In recent years, it has been changed from theory into a practical stage gradually, and it provides a new way for modern decorating and lighting [1~3]. Fiber-optic lighting offers a unique new way for the decoration and lighting with pro-environment, safety, energy saving, convenient and high efficiency [1~4]. At the same time, fiber-optic lighting has some advantages that general lighting can not provide. For example, the spread of light can be flexible, and light and electric is separated. It only has the visible light and no infrared or ultraviolet light, and it is colorful and versatile. Because of these virtues, fiber optic decorative lighting is widely used in advertising, landscape design, entertainment, industrial field, medical treatment, museums, mines and other special lighting occasions[4~7]. It is prospective in the field of decorative lighting in the 21st century.

2. Constitution of fiber-optic lighting system
Fiber-optic lighting system is mainly constituted of light source, couple and fiber, as shown in Fig.1. Light source provides energy for the whole lighting system, and couplers could couple light into the fiber to transmit. Light transmitting in optical fiber leaks out at the fiber-optic loops by the certain ratio for lighting, because the cladding of fiber loop is removed partially. In this way, we could control the leakage rate of the fiber-optic loops, the reflectivity of the reflector to obtain a good effect in decoration lighting, and satisfy the requirements of modern decorative lighting.
Figure 1. The configuration of the fiber lighting system  Figure 2. amplificatory picture of fiber loop

The configuration of the fiber-optic lighting system is shown as Figure 1. It contains one light source at initial of fiber, one coupler, fiber and one reflector at end of fiber. Light generating from the light sources is coupled into the optical fiber with coupler, which leaks out at the fiber loop \( L_n \) \( (n = 1, 2, 3 \ldots) \) for lighting and decoration\(^7\). Then the leftover part light at the end is reflected back to fiber to reuse by reflector. Fig. 2 is an enlarged view of the optical fiber loop. The loop which the cladding layer is removed partially is made up of a circle fiber. The paper analyzes the key factors affecting the lighting power and uniformity of the distributed fiber lighting system, such as light leakage rate of fiber loops, and the reflectivity of reflector. The above parameters are studied with MATLAB7.0 software.

3. Simulating the performance of with Rsoft software

The multimode step index fiber is used and the transmission and loss of the visible light in fiber whose core layer is corroded is simulated and analyzed. The parameters of the multimode step-index fiber are as follows: core layer diameter is 105 \( \mu \)m, cladding layer diameter is 125 \( \mu \)m, coating layer is 250 \( \mu \)m, core index is 1.4662, and cladding index is 1.45. The incident light is He-Ne laser, and wavelength is 632.8nm.

The simulation for different diameter and length of corrosive fiber shows: holding the corrosive diameter, the power loss in fiber core layer is not same for different corrosive length. And the power has loss at ends of corrosive part. According to the theory of optical waveguide \(^8\), the loss at the initial part of corrosion is light leak that the light transforms from the larger diameter of fiber core into smaller one, which belongs to the lighting power, but the end does not. According to the optical mode theory, the power ratio of fiber core can be expressed as \(^8\)

\[
\eta_m(m) = 1 - \frac{U^2}{V^2} (1 - \kappa)
\]

(1)

Where \( V \) is the normalized frequency, \( V = k_0 a (n_{co}^2 - n_{cl}^2)^{\frac{1}{2}} \), \( U \) is normalized phase constants, \( U = a (k_0^2 n_{co}^2 - \beta^2)^{\frac{1}{2}} \).

Based on the simulation results, the loss is not linear relationship. Holding the length of corrosion, the loss increases with decreasing of diameter of core layer. The curve is obtained as figure 3 for loss of initial point.
4. Simulation and analysis

We assume that the optical power coupled into the fiber is \( p_0 \) (unit: W), the distance between light source and the nearest loop is \( a \) (unit: m), the adjacent distance is \( b \) (unit: m), the loss of optical fiber is \( \alpha \) (units: \( 1/m \)), the leakage rate of the fiber-optic loops is \( \mu \), the reflectivity of reflector is \( r \), and the number of optical fiber loops is \( n \) \((n = 1, 2, 3, \ldots)\). Then we can get lighting power \( W_{1k} \) (unit: W) of the \( k \) \((k=1,2,3,\ldots, n)\) fiber loop by calculating and simulation without reflector as follows:

\[
W_{1k} = p_0 e^{-\alpha \left[ a + (n-1)b \right]} (1 - \mu)^{n-1} \mu \tag{2}
\]

The lighting power \( W_{2k} \) (unit: W) of the \( k \) \((k=1,2,3,\ldots, n)\) fiber loop by calculating and simulation with reflector as follows:

\[
W_{2k} = p_0 e^{-\alpha \left[ a + (k-1)b \right]} (1 - \mu)^{k-1} \mu + p_0 re^{-\alpha \left[ a + (2n-k-1)b \right]} (1 - \mu)^{2n-k} \mu \tag{3}
\]

From the above equations, we can obtain lighting power of each loop.

In this fiber-optic lighting system, \( \mu \) and \( r \) are varied parameters. Other parameters can be set according to the actual conditions as follows. The light source power coupled into the fiber is \( p_0 = 200W \); the distance between light source and the nearest loops is \( a=3m \); the number of fiber loops is \( n=20 \); the adjacent distance is \( b=1 \) meters. Range of the visible light, the minimal loss of POF made by PMMA-d8 is 19.4dB/km at the 680nm\[9\], so we can set the attenuation of fiber-optic as 40dB/km, and it could be converted into attenuation coefficient \( \alpha = 9.21 \times 10^{-3} / m \). Based on the above formula (1), we use MATLAB 7.0 software to analyze the effects of these three variable parameters and illumination uniformity of lighting system.

4.1 Analysis on the light leakage rate \( \mu \) of fiber loops

Holding \( r = 0.95 \) and other parameters, and varying \( \mu \), we can obtain variable power curve of fiber loops through simulation and calculation with MATLAB when \( \mu=0.080 \), \( \mu=0.050 \), \( \mu=0.035 \), as figure 3.
Figure 4. Optical power curve without (a) reflector and with (b) reflector for different $\mu$.

It is shown from Fig 4. , the difference of each loop's lighting power is large with large $\mu$, regardless of whether there is reflector at the end of fiber. The lighting power curve bends obviously, then the uniformity of lighting power is poor, but the average power is larger. When the value of $\mu$ is small, the difference of each loop's lighting power decreases. So the curve is close to a flat line, and the uniformity is very well. As it is shown in the fig.3, the curve signed by "•" indicates the lighting power with $\mu=0.05$. Although the average power corresponding to the two curves above is very large, the difference of the variable points' power is large too, and the uniformity is poor. The curve below is close to a flat line, but the power of loops is too small. In the other words, the average power is small and the lighting effect is poor. At the same time, we can see from fig.3, that the power of loops decreases seriously with $\mu$ reducing. Thus, we should contrive to select a larger $\mu$ and ensure the effective power and average power is better.

4.2 Analysis on the reflectivity $r$ of the end reflector

The function of reflector is to reuse the leftover power continuely in fiber. Because of various technology, the reflectivity of reflector has difference, which would lead to different effects to the lighting power and uniformity. Using advanced precision technology, the reflectivity of reflector can achieve 99.9% above in domestic [10]. So we can set $r = 0.95$, $r = 0.90$ and $r = 0.80$, then we carry out the numerical simulation and obtain the results as figure 4.

Figure 5. Optical power curve with different reflectivity
In figure 5, the lighting power of each loop increases after Coating film reflector, especially at the end. The increased lighting power has some difference with various reflectivity. Namely, the larger the reflectivity is, the more the increasing is. Conversely, the power increases gradually. Therefore, we should choose larger reflectivity to get better lighting power and uniformity.

5. Conclusions

The lighting power and lighting uniformity of a distributed fiber-optic lighting system with reflector are simulated and analyzed with MATLAB 7.0 and Rsoft software. During the numerical simulation, we study the parameters one by one with varying a parameter and holding other parameters. First, the relationships of the lighting power and uniformity of the distributed fiber lighting system with light leakage rate of fiber loops is analyzed. The next is reflectivity of the end reflector. The simulation results show that, the light leakage rate \( \mu \) of fiber loops, the reflectivity of reflector in the fiber-optic lighting system have an obvious effect on the lighting power and uniformity, and the high lighting power and good uniformity are conflictive objects. The compromising effect is obtained on the condition that the light leakage rate is 0.05 and the reflectivity of reflector is 95%.

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