Dust concentration photoelectric detection bit error rate model and performance analysis

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To improve the photoelectric detection sensitivity and testing precision of industrial dust concentration, this paper proposes a new testing dust concentration method by using multi-laser photoelectric detection principle, establishes the multi-laser photoelectric detection testing model and gives the calculation function of dust concentration. According to the scattering characteristic of dust particles and the output current of photoelectric receiver, research and set up the bit error rate model of dust concentration testing system, analyze the relation of the signal to noise ratio and bit error rate; From the scattering radiation flux of dust particle and output current of photoelectric receiver in the dust concentration testing system of using multi-wavelength of laser, give the correlative function of actual dust concentration and bit error rate. Through the calculation and experiment analysis, the results shows that the bigger the wavelength of laser, the higher the signal to noise rate of photoelectric receiver, the smaller the bit error rate, and the more precise the testing data of dust concentration. By analyzing the experimental data of dust concentration in different detection distances and bit error rates, the results indicate the established bit error rate model is effective and reasonable in the short-distance dust concentration testing system.

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Keywords: Dust concentration, Photoelectric detection sensitivity, Bit error rate, Testing precision

1. Introduction

The industrial dust concentration is concerned about the health of the people's livelihood, especially in the coal mine and sandstorm's environment, dust particles not only pollute the environment, but harm people's health in different degrees, the measurement of industrial dust concentration is increasingly important in the current coal mine industry.

At present, the main testing method of dust concentration has capacitance method, light absorption method, light scattering method, and ultrasonic method [1-3]. Among them, optical testing method has the characteristics of good testing effect and fast testing speed in dust concentration testing system, but the mutative environment affects dust concentration testing, makes the testing value of dust concentration unstable, the main reason is that we merely consider the relationship between the output current of photoelectric detection receiver and dust concentration, have not considered the detection probability and the bit error rate and the signal to noise ratio of photoelectric detection system [4].

Therefore, it is very necessary to construct a new calculation model of dust concentration from the bit error rate of photoelectric detection system, provide a new theoretical model for improving the testing dust concentration in industrial dust environment. According to the scattering characteristics of industrial dust particles [5-6], this paper proposes a light scattering method to measure dust concentration, uses the laser and the two photoelectric detection receivers to design detection device to test dust concentration in the region, is able to supply scientific basis for the multi-region testing of atmospheric dust concentration.

2. Dust concentration photoelectric detection methods and testing principles

The distribution of dust particles is uneven, particularly in the haze weather, causes dust concentration irregular [7], so the dust concentration testing system by using light scattering method has the low sensitivity and high bit error rate in the wind, rain, snow, haze weather [8]. In order to obtain the accurate value of dust concentration, we use multi-sensor photoelectric detection, add the multi-wavelength of laser, construct the dust concentration testing system, as shown in Fig. 1.

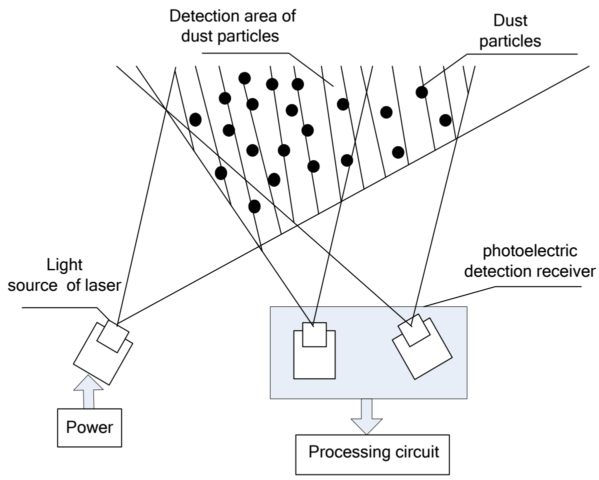

Fig. 1. Dust concentration testing system based on laser reflection principle

The dust concentration testing system is composed of the laser, the photoelectric detection receiver and the processing circuit. We use two photoelectric detection receivers to form the photoelectric detection field of view, construct detection area of dust particles by intersecting with laser beam, and obtain the testing value of dust concentration according to the scattering characteristic of dust particles in the effective detection area.

From Fig. 1 can be seen that, the detection distance is unchanging, the larger the detection area of dust particles, the higher the radiation energy and the bigger the output current of photoelectric detection receiver. Assuming the noise of dust concentration testing system is relatively constant, the output current of photoelectric detection receiver is bigger, the signal to noise ratio of photoelectric detection receiver is higher, the bit error rate of photoelectric detection is lower, the testing value of dust concentration is more accurate.

In order to obtain the correlation function between the output current of photoelectric detection receiver and multi-wavelength of laser, we must analyze and establish the model of output current of photoelectric detection receiver under specific light source wavelength of laser. Assuming that E is the illumination of radiation of dust particles under fixed laser emission power and certain detection distance, the radiation energy of sensitive surface of photoelectric detection receiver is from the reflection of dust particles, it is defined in equation (1).

$$E_1 = E \cdot S \cdot \cos\theta \tag{1}$$

In (1), E_1 is the radiation energy of sensitive surface of photoelectric detection receiver from the reflection of dust particles. S is the reflection area of dust particles, θ is the scattering angle that incident light reflect from the surface of dust particles to the photoelectric detection receiver. The atmospheric attenuation coefficient has certain effect on the scattering radiation flux of dust particles, the photoelectric detection receiver obtains the scattering radiation flux under different detection distance, it can be acquired by the formula (2).

$$\Phi = \frac{\cos\theta}{\pi} \cdot E \cdot S \cdot \cos\theta \cdot \frac{1}{L^2} \cdot \delta \tag{2}$$

In (2), Φ is the scattering radiation flux, L is the detection distance, δ is the atmospheric attenuation coefficient.

Supposing that t_0 is the retention time from dust particles to photoelectric detection receiver, N is the photon's number that dust particles reflect to photoelectric detection receiver, we consider the retention time has an influence on the photon's number of photoelectric detection receiver, based on formula (2), the photon's number of photoelectric detection receiver is shown in formula (3).

$$N = \Phi \cdot A_0 \cdot f_s \cdot q_s \cdot \tau_o \cdot t_0 \tag{3}$$

In (3), A_0 is the receiving area of photoelectric detection receiver, f_s is the filter coefficient of photoelectric detection receiver, q_s is the average quantum efficiency of photoelectric detection receiver, τ_o is the transmittance of optical lens [9].

If g is the number of dust particles of detection area, P_S is the average optical power that dust particles reflect to the photoelectric detection receiver, in order to express the output current of photoelectric detection receiver under specific light source wavelength of laser, combine with formula (3), it can be calculated by formula (4).

$$i' = \sum_{i=1}^{g} k \cdot P_S \cdot R \cdot \frac{N}{t_1} \tag{4}$$

In (4), k is a constant, $P_S = \beta \cdot P_0 \cdot \cos\theta$, β is the reflection coefficient, P_0 is laser emission power, R is the responsivity of photoelectric detection receiver, $R = \eta e\lambda/(hc)$, η is the quantum efficiency of photoelectric detection receiver, λ is the light source wavelength of laser, e is the electron charge, $e = 1.6\times10^{-19}C$, h is the Planck constant, $h = 6.625\times10^{-31} J/s$, c is the speed of light, $c = 3\times10^8 m/s$, t_1 is the time that the photocurrent turn into current [10-11].

In order to establish the relationship between the dust concentration and bit error rate, we should discuss and set up the dust concentration model. Assuming that the dust particles is a single particle size in the unit volume, the relationship between intensity of incident light and intensity of reflected light can be expressed by formula (5).

$$I = I_0 e^{-\frac{1}{4}N_v \pi L d^2 K(\lambda,m,d)} \tag{5}$$

In (5), I is the intensity of reflected light, I_0 is intensity of incident light, K is the extinction coefficient, which is related to light source wavelength, refractive index and particle size of dust particles [12-13], among, m is the refractive index, d is the particle size of dust particles, N_v is the particle number concentration of dust particles.

The ratio of incident light's intensity to reflected light's intensity is took logarithm, the formula (5) is changed into formula (6).

$$\ln\left(\frac{I_0}{I}\right) = \frac{\pi}{4} d^2 N_v K L \tag{6}$$

We can obtain the particle number concentration of dust particles by formula (6), it is expressed by formula (7).

$$N_v = \ln\left(\frac{I_0}{I}\right) \frac{4}{\pi d^2 K(\lambda,m,d) L} \tag{7}$$

Supposing that the dust particles is spherical particles, the mass concentration of dust particles can be calculated by formula (8).

$$
\begin{aligned}
M_\upsilon &= N_\upsilon \cdot \rho \cdot V = N_\upsilon \cdot \rho \cdot \frac{4\pi}{3}\left(\frac{d}{2}\right)^3 \\
&= \ln\left(\frac{I_0}{I}\right)\frac{4}{\pi d^2 K(\lambda,m,d)L}\cdot \rho \cdot \frac{4\pi}{3}\left(\frac{d}{2}\right)^3 \\
&= \ln\left(\frac{I_0}{I}\right)\frac{2\rho d}{3LK(\lambda,m,d)}
\end{aligned} \tag{8}
$$

In (8), M_υ is the mass concentration of dust particles (it is called dust concentration for short), ρ is the density of dust particles, V is the volume of dust particles.

In the dust concentration testing system, the bit error rate of photoelectric detection affects the testing value of dust concentration [14], in order to improve the testing accuracy and detection performance of dust concentration testing system, establish the actual dust concentration model. According to the formula (8), the correlation function between dust concentration and bit error rate can be expressed by formula (9).

$$M = M_\upsilon \cdot (1-P) \tag{9}$$

In (9), M is the actual value of dust concentration, P is the bit error rate.

3. The model and analysis of bit error rate of photoelectric detection system

3.1. Bit error rate model of photoelectric detection system

Assuming that the photoelectric detection system contains noise, formula (4) shows the output current of photoelectric detection receiver under specific light source wavelength of laser, the complete output current of photoelectric detection receiver should include the noise of photoelectric detection system and output current of photoelectric detection receiver. Based on formula (4), the complete output current can be described by formula (10).

$$i = i_N + i' \tag{10}$$

In (10), i_N is the noise current of photoelectric detection system, i' is the output current of photoelectric detection receiver.

The noise mainly includes scattered noise, thermal noise and background light's noise [15-17]. If σ_{SN} is the scattered noise, σ_{SN}^2 is its variance, $\sigma_{SN}^2 = 2eBi'$, BW is the bandwidth of detector's subsequent filter [18]. The internal electrons of an object above freezing generate the thermal noise by the non-regular thermal motion, σ_{TN} is the thermal noise, σ_{TN}^2 is its variance, $\sigma_{TN}^2 = 4K_B TBW / R_L$, K_B is the Boltzman constant, its value is $1.38\times10^{-34} J/K$, T is the temperature of equivalent noise, R_L is the load impedance, σ_{BN} is the background light's noise, σ_{BN}^2 is its variance, $\sigma_{BN}^2 = 2eRP_B BW$, P_B is the power of background light.

According to the superposition theorem of noise, the variance of total noise's current can be calculated by formula (11).

$$\sigma_N^2 = \sigma_{SN}^2 + \sigma_{TN}^2 + \sigma_{BN}^2 \tag{11}$$

In (11), σ_N^2 is the variance of total noise's current.

The signal to noise ratio of photoelectric detection receiver is the ratio of the photoelectric detection receiver's output current to the mean-square value of total noise's current, it is shown in formula (12).

$$R_{SN} = \frac{i'}{\sigma_N} \tag{12}$$

In (12), R_{SN} is the signal to noise ratio of photoelectric detection receiver.

Combining the formulas (4) and (11) and (12), the signal to noise ratio can be expressed by (13).

$$R_{SN} = \frac{RP_S}{\sqrt{2eBWR(P_S + P_B) + \dfrac{4K_B TBW}{R_L}}} \tag{13}$$

The dust particles reflect to the photoelectric detection receiver, which generate the average optical is larger, the scattered noise is dominant status in the photoelectric detection system, we ignore the influence of thermal noise and background light's noise, the formula (14) shows the simplified model of signal to noise ratio.

$$R_{SN} = \sqrt{\frac{RP_S}{2eBW}} = \sqrt{\frac{\eta\lambda P_S}{2hcBW}} \tag{14}$$

Combine formulas (12) with (14),we can find that the signal to noise ratio is proportional to output current of photoelectric detection receiver when the noise of photoelectric detection system is relatively constant, the output current is related to the receiving area of photoelectric detector and the responsivity of photoelectric detector. We also discover that the signal to noise ratio is proportional to light source wavelength of laser, is proportional to average optical power of photoelectric detector. Because of $P_S = \beta \cdot P_0 \cdot \cos\theta$, the average optical power is proportional to laser emission power, the laser emission power is proportional to signal to noise rate. In order to improve signal to noise ratio, we can enlarge the receiving area, increase the light source wavelength, add the laser emission power under the case of personal safety.

The photoelectric detection receiver's output current and the signal to noise ratio affect the bit error rate of photoelectric detection system, the bit error rate model is can be expressed by formula (15).

$$P = \frac{1}{2}\left[erfc\left(\frac{i'}{2\sqrt{2}\sigma_N}\right)\right] = \frac{1}{2}erfc\left(\frac{R_{SN}}{2\sqrt{2}}\right) \tag{15}$$

In order to reduce the bit error rate, we improve the signal to noise rate, or we increase output current of photoelectric detection receiver by enlarging the receiving area of photoelectric detector when the noise of photoelectric detection system is relatively constant.

Based on formula (14) and (15), the correlation functions of bit error rate, laser emission power and light source wavelength is obtained, it can be expressed by equation (16).

$$P = \frac{1}{2} erfc \frac{1}{4} \cdot \sqrt{\frac{\eta \cdot \lambda \cdot \beta \cdot P_0 \cdot \cos\theta}{h \cdot c \cdot BW}} \qquad (16)$$

In order to reduce the bit error rate, select a much bigger of light source wavelength by using multi-wavelength of laser, or increase effectively laser emission power when we design the process of dust concentration testing system.

3.2. Detection performance analysis of photoelectric detection system

The light source wavelength has effect on the dust concentration and the bit error rate; we change the light source wavelength, also affect the testing value of actual dust concentration. Supposing that $\lambda \in (\lambda_1, \lambda_2)$, the photoelectric detection receiver obtain the scattering radiation flux, it is defined in equation (17).

$$\Phi(\lambda) = \int_{\lambda_1}^{\lambda_2} \frac{\cos\theta}{\pi} \cdot E \cdot S \cdot \cos\theta \cdot \frac{1}{L^2} \cdot \delta d\lambda \qquad (17)$$

The photoelectric detection receiver obtains the photon's number, which is varied by the changed light source wavelength, it can be calculated by function (18).

$$N(\lambda) = \Phi(\lambda) \cdot A_0 \cdot f_s \cdot q_s \cdot \tau_o \cdot t_0 \qquad (18)$$

Contact with the light source wavelength, the output current of photoelectric detection receiver under the changing light source wavelength can be expressed by formula (19).

$$i' = \sum_{i=1}^{g} k \cdot P_0 \cdot R \cdot \frac{\Phi(\lambda) \cdot A_0 \cdot f_s \cdot q_s \cdot \tau_o \cdot t_0}{t_1} \qquad (19)$$

Combining the formulas (9), (15) and (19), we obtain the calculation model of actual dust concentration by using multi-wavelength of laser, it is shown in (20).

$$M(\lambda) = \ln\left(\frac{I_0}{I}\right) \frac{2\rho d}{3LK(\lambda, m, d)} \cdot (1 - \frac{1}{2} erfc \frac{1}{4} \cdot \sqrt{\frac{\eta \cdot \lambda \cdot \beta \cdot P_0 \cdot \cos\theta}{h \cdot c \cdot BW}}) \qquad (20)$$

It is known from (20) that laser emission power, light source wavelength and detection distance affect simultaneously the testing accuracy of dust concentration.

4. Calculation and experiment analysis

4.1. Calculation analysis

According to the testing system of dust concentration based on laser reflection principle and the correlative model of bit error rate and dust concentration, we obtain the result that bit error rate and dust concentration are nonlinear positive proportional function. We set up the testing platform, design the module of laser detection transceiver, and employ the optical imaging module by using short focus lens. Among, the focal length of lens is 16 to $24mm$, the sensitive surface of photoelectric detection receiver is $3mm \times 3mm$, the response's wavelength is 0.4 to $1.1\mu m$, the detection response is $10^{-7}\mu s$, and the biggest emission power of laser is $10W$. Based on the hardware platform, we calculate the relationship between dust concentration and detection distance, get the relation of bit error rate and light source wavelength and laser emission power, obtain the relation of dust concentration and bit error rate.

According to the formulas (5)-(8), we calculate the dust concentration at different detection distance, when the detection distance is changed; the testing value of dust concentration has also had an impact. Fig. 2 is relation curve of dust concentration and detection distance under the different light source wavelength, M_v expresses the dust concentration in Fig. 2.

If the density of dust particles is $7.9\,g/cm^3$, the diameter of dust particles is $20\mu m$, the light source wavelength of detector is $400nm$, $500nm$, $800nm$ respectively, the detection distance is 0.05 to $0.5km$. From Fig. 2 can be seen that the condition of three different light source wavelength, with increment of detection distance, the dust concentration gets lower, when the detection distance is more than $0.45km$, the changed value of dust concentration is small, because the detection distance is farther, the optical properties of dust particles makes radiation energy of photoelectric detection receiver change smaller.

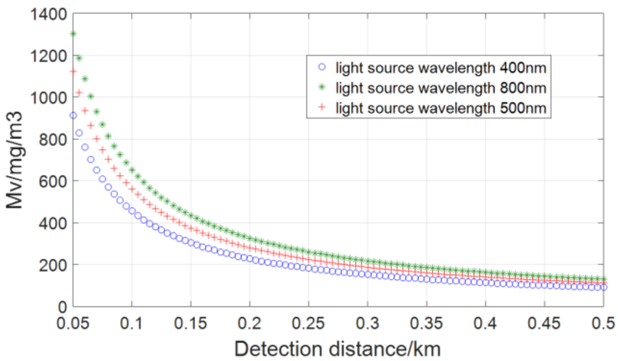

Fig. 2. The relation curve of dust concentration and detection distance under the different light source Wavelength

Based on the formulas (11)-(16), we can find that light source wavelength and laser emission power are closely related to the photoelectric detection system. Fig. 3 and Fig. 4 show the relation curves of bit error rate and light source wavelength under different reflection coefficient, Fig. 5 and Fig. 6 show the relation curves of bit error rate and laser emission power under different reflection coefficient. BER shows bit error rate in Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8 and Fig. 10.

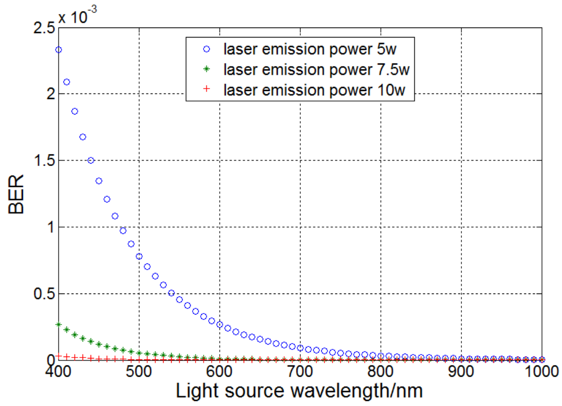

Fig. 3. $\beta = 0.1$, *the relation curve of bit error rate and light source wavelength*

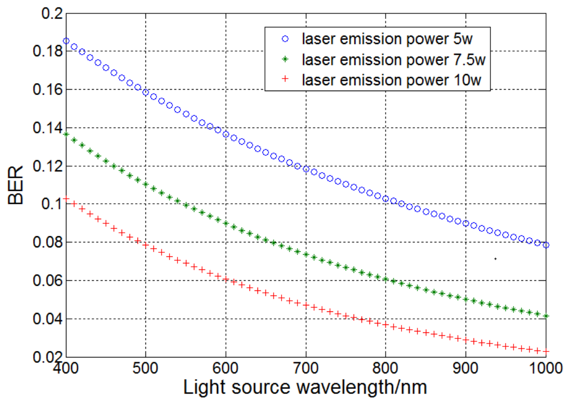

Fig. 4. $\beta = 0.01$, *the relation curve of bit error rate and light source wavelength*

When the quantum efficiency of photoelectric detector is 0.9, $\cos\theta$ is 0.707, the bandwidth of detector's subsequent filter is $2MHz$, the light source wavelength is assumed from 400 to 1000*nm*, the laser emission power is 5*W*, 7.5*W*, 10*W* respectively. Fig. 3 is the calculation result when the reflection coefficient is 0.1, Fig. 4 is the calculation result when the reflection coefficient is 0.01, from the results of Fig. 3 and Fig. 4 that with increment of light source wavelength, bit error rate rapidly decreases, when the light source wavelength is greater than 800*nm*, the bit error rate is very small. In order to improve detection performance of photoelectric detection system, reduce bit error rate, select near infrared photoelectric detection receiver.

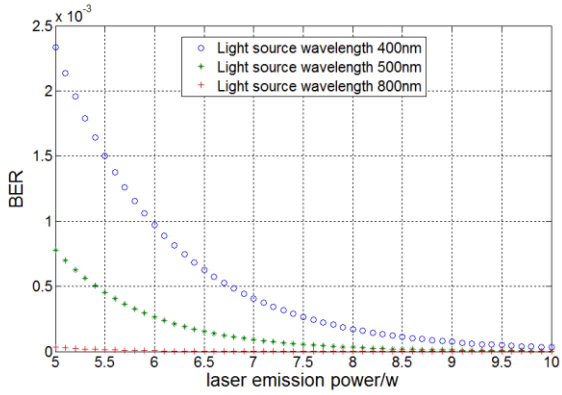

Fig. 5. $\beta = 0.1$, *the relation curve of bit error rate and laser emission power*

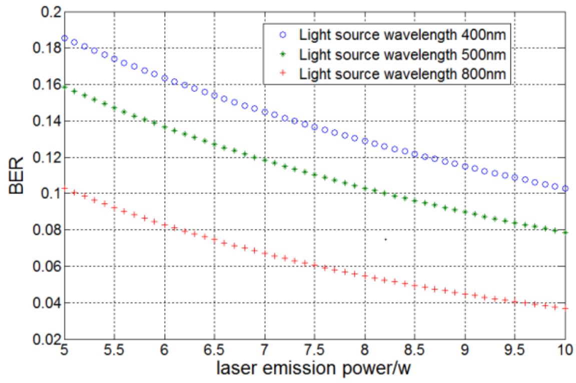

Fig. 6. $\beta = 0.01$, *the relation curve of bit error rate and laser emission power*

When the range of laser emission power is from 5 to 10*W*, the light source wavelength is 400*nm*, 500nm, 800*nm* respectively, if the reflection coefficient is 0.1, the result is shown in Fig. 5, if the reflection coefficient is 0.01, the result is shown in Fig. 6, the results show that the larger laser emission power, the smaller bit error rate, we can obtain the accurate value of dust concentration under certain detection distance. When we design the dust concentration testing system, improve effectively laser emission power to reduce bit error rate.

When light source wavelength and laser transmission power change synchronously, the bit error rate has greater impact. Fig. 7 and Fig. 8 give the relation curve of bit error rate, light source wavelength and laser emission power.

Fig. 7 is the calculation result when the reflection coefficient is 0.1, Fig. 8 is the calculation result when the reflection coefficient is 0.01. From the figures can be found that dust concentration is related to bit error rate, bit error rate is affected by light source wavelength and laser emission power. The higher laser emission power, the smaller bit error rate, the precision of the dust concentration is higher under certain light source wavelength. In order to improve the testing accuracy of dust concentration, ensure a certain bit error rate, need to improve detection performance of system, reduce noise of system, improve signal to noise ratio of photoelectric detection receiver.

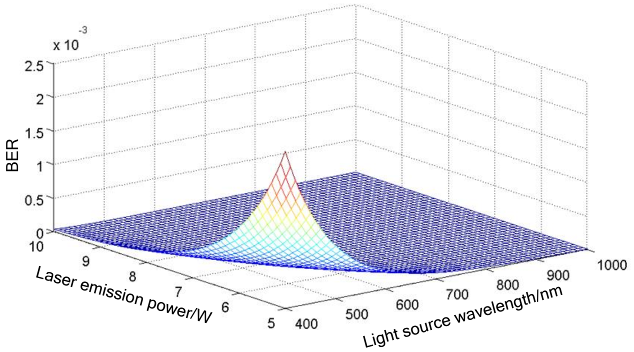

Fig. 7. $\beta = 0.1$*, the relation curve of bit error rate, light source wavelength and laser emission power*

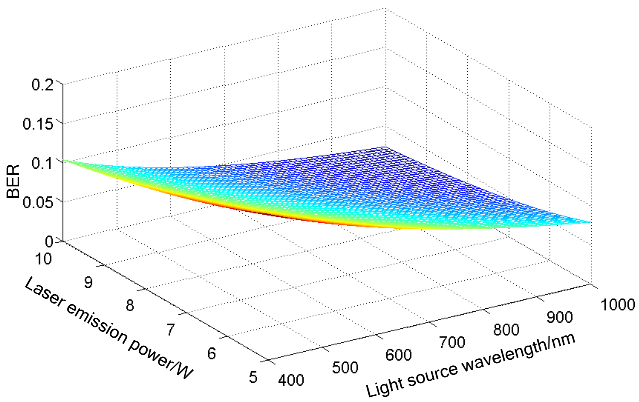

Fig. 8. $\beta = 0.01$*, the relation curve of bit error rate, light source wavelength and laser emission power*

Assuming that light source wavelength is 400 to 1000*nm*, reflection coefficient is 0.1 and 0.01 respectively, according to the formulas (17)-(20), Fig. 9 shows the relation curve of dust concentration and detection distance. M expresses the actual dust concentration in Fig. 9 and Fig. 10.

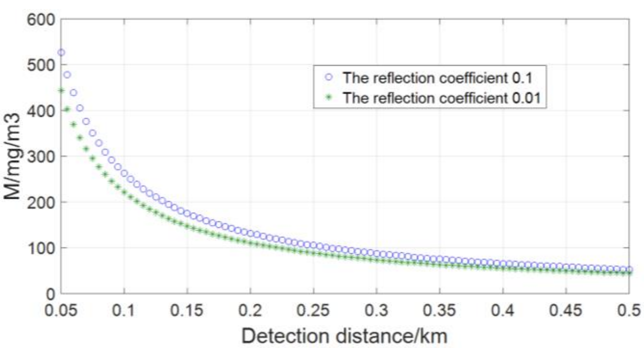

Fig. 9. The relation curve of dust concentration and detection distance

Fig. 9 illustrates the relation of dust concentration and detection distance, the noise of photoelectric detection system is constant under certain optical system. According to the principle of optical imaging system, the detection distance is farther, the energy of photoelectric detection receiver sensing surface is constant, the energy is from the radiation of dust particles in the region. From Fig. 9 can be found that when detection distance is greater than 0.4km, dust concentration is close to 50 mg/m^3 , detection distance is smaller, dust concentration has greater change, especially detection distance is 0.05 to 0.1km, the range of dust concentration is about from 200 to 500 mg/m^3 . Because of the optical properties of dust particles, the detection distance is smaller, the output of photoelectric detection receiver is bigger under the constant condition of optical system.

Fig. 10 gives the relation curve of dust concentration and bit error rate, we can observe that the lower bit error rate, the higher the dust concentration, conversely, the lower, meantime, with increment of detection distance, the dust concentration is lower. When the detection distance is more than 0.25km, the change of bit error rate has a little effect on the measurement of dust concentration, the result shows the detection distance is farther, because of the optical properties of dust particles, the energy of photoelectric detection receiver has the smaller change, only the detection distance is smaller, the tesing result of dust concentration has more obvious change. Therefore, we need to improve the detection sensitivity when we design the testing platform of dust concentration based on laser reflection principle. In order to obtain accurate measurement of dust concentration, we can increase the laser emission power, add the aperture of optical lens, improve the gain of detection circuit, effectively change the remote detection of dust concentration to obtain scientific values of dust concentration. Through the quantitative calculation, we can find that that the model of bit error rate and dust concentration can accurately reflect the distribution characteristics of dust concentration in the project, in order to establish the testing system of atmospheric dust concentration, we need multi-region and multi-point detection to obtain scientific data about atmospheric dust concentration in different regions.

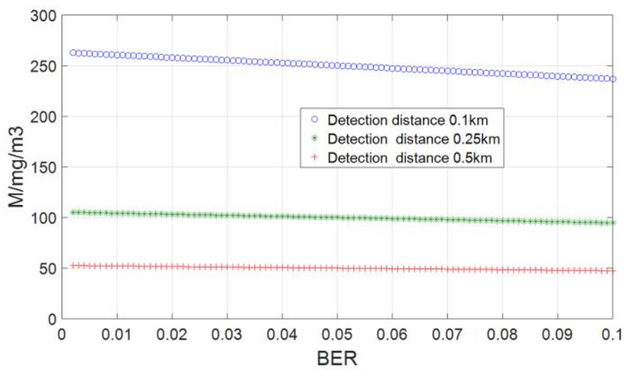

Fig. 10. The relation curve of dust concentration and bit error rate under the different detection distance

4.2. Experiment analysis

Based on the testing platform of dust concentration, we collect these testing values of dust concentration under different detection distance and different bit error rate, when the photosensitive surface of photoelectric detection receiver is about $3mm*3mm$, the light source wavelength of photoelectric detector is about 680*nm*, the detection response is $10^{-7}\mu s$, the laser emission power is about 8*W*, we obtain the experimental data of dust concentration, it is shown in Table 1.

Table 1. The experimental data of dust concentration

Detection distance (km)	Dust concentration (mg/m3)	Bit error rate
0.1	260.4	0.0112
0.15	170.8	0.0271
0.2	125.1	0.0511
0.25	97.85	0.0715
0.5	55.24	0.0843

In Table 1, when detection distance is equals to 0.1 km, bit error rate is about 0.0112, dust concentration can reaches 260.4 mg/m^3. When detection distance is about 0.15 km, bit error rate is about 0.0271, dust concentration is 170.8 mg/m^3. When detection distance is about 0.5 km, bit error rate is about 0.0843, the value of dust concentration diminishes 205 mg/m^3 than detection distance is 0.1 km. We can observe that the shorter detection distance, the more precise dust concentration, because the bit error rate is smaller, we suggest atmospheric dust concentration employ the short-distance and multi-point detection. A part of experimental data are inconsistent with simulation result, the main reason is environmental characteristics changed greatly, causes the measurement of dust concentration bring in greater deviation, the experimental data can basically express the atmospheric dust concentration in the region, the paper designs the calculation model and method is able to supply scientific basis for the multi-region and multi-point detection of atmospheric dust concentration.

5. Conclusions

This paper uses the dust concentration testing device with laser transmitter and receiver, analyzes the testing principle of dust concentration, establishes the model of radiation's characteristics that dust particles reflect to sensitive surface of photoelectric detection receiver, gets the calculation function of output current of photoelectric detection receiver according to the optical properties of dust particles, gives the model of dust concentration under the certain light source wavelength, obtains the correlation function between dust concentration and bit error rate according to the scattering characteristics of dust particles,

In accordance with the multi-wavelength of laser, deduces the calculation model of actual dust concentration. Through the calculation and analysis, the dust concentration decrease with the increment of detection distance, when the detection distance is smaller, dust concentration has greater change by bit error rate. We establish the calculation model of short-distance dust concentration, which can provide the design and analysis basis for making better the testing system of the atmospheric dust concentration.

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