Research on Photoelectric Detection System Applying to UV-VIS Spectroscopy Water Quality Monitoring System

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Abstract. In order to solve the problem of low luminous flux and quantum efficiency of the photoelectric detection system of UV-Visible spectroscopy water quality monitoring, a photoelectric detection system with high flux, stray light and enhanced sensitivity to ultraviolet band has been developed. The study of simulation design is carried out by using ZEMAX optical analysis software. According to the theoretical calculation of water absorption characteristic band, concave grating is used as the light splitting element. Through reasonable optical design and compact structure layout, the stable operation in spectral range of 200 to 800nm is achieved. The simulation results show that the resolution of the photoelectric conversion system is better than 2nm, which meets the requirements of the water quality detection of UV-Visible spectrum.

Introduction

With the rapid development of social economy, environmental pollution has increasingly threatened people's life and health, and water pollution has become one of some very serious problems which are faced by countries all over the world now. In view of the serious water pollution problem, it is of great significance to establish a real-time and on-line monitoring system for water quality[1]. Based on UV-visible spectrum water quality monitoring technology, the multi-parameter measurement of water quality can be realized quickly[2]. It has the advantages of simple operation, low cost, secondary pollution, online and in situ measurement, and has become an important development direction of water quality monitoring instrument[3]. The existing water quality monitoring systems mainly use spectrometers as a photoelectric detection system. In particular, when modern water quality monitoring technology puts forward the demand of micro portable, low-cost, real-time online, in situ multi-parameter measurement for instrument and equipment, the design and manufacture of such optical equipment has become the key technology of spectral method for water quality measurement[4,5].

At present, the production of photoelectric detection system is mainly monopolized by foreign companies, such as Avantes in Holland, Ocean Optics and Photo Research in the US. Domestic research in the field of manufacturing equipment started in recent years, there are still many shortcomings, such as low flux and sensitivity, stray light interference. It is too difficult to meet the "13th Five-Year" the instrument of localization, intelligent demand, and the River Chief System on the water environmental governance efficiency.

Based on these situations, aiming at the design of ultraviolet visible spectrum water quality monitoring and monitoring system with independent intellectual property rights, the flat field holographic concave grating is used as the core optical component. Through the theoretical calculation of the initial structural parameters, and using ZEMAX optical analysis software, a reasonable layout of the optical path is achieved. Finally, the design of the broadband and high
resolution photoelectric detection system has been realized, which provides a basis for the subsequent prototype design and production.

System Principle and Composition

The photoelectric detection system of UV-visible spectrum water quality detection mainly includes optical system, detector, signal acquisition and processing module, and data transmission module. The principle of the system is shown in Figure 1.

![Figure 1. Schematic diagram of photoelectric detection system.](image)

The light source sends out composite light, which is transmitted through the sample pool and becomes a signal light. Then, it enters the optical system through the slit, and it is obtained by splitting the flat field holographic concave grating and obtaining the monochromatic light arranged sequentially in different wavelengths. The online array CCD detector faces the image, and the detector converts the optical signal into electrical signal. The signal acquisition and processing module collects, preprocesses and amplifies the output signal of the detector and gets the corresponding spectral data. The data transmission module transmits the spectral information to the computer through the communication interface. Through the analysis of the spectrum processing software, the components and content information of the measured water can be obtained, so as to achieve the purpose of quantitative analysis of the water quality parameters.

Design and Simulation of Optical System

The optical system is the core of the front end of the photoelectric detection system, and its imaging quality directly determines advantages and disadvantages of the system. The most commonly used optical structures are the Czerny-Turner structure based on the plane grating and the flat field holographic concave grating based on the Roland circular structure[6,7]. The former is compact in structure and low in cost, but it involves many optical components, it is very difficult to install and adjust, and the loss of luminous flux is great. The concave grating of the latter has both optical and imaging functions, which consists of an optical system with only one optical surface, but there is also a small lack of spectral range. In this study, the concave grating structure is chosen as the front-end optical system of the spectral analyzer. The relevant theoretical research and structural calculation methods have been done by some previous institutions. Take Roland circular as the initial structure, and then step by step to the flat field. According to the geometric theory of holographic concave grating, the series expansion of the optical path function of any point on the concave grating is shown as[8]:

\[
F = F_{oo} + yF_{10} + \frac{1}{2} y^2F_{20} + \frac{1}{2} z^2F_{02} + \frac{1}{2} yzF_{30} + \frac{1}{2} y^2 z^2F_{40} + \frac{1}{8} y^4 F_{40} + \cdots,
\]

(1)

where \(y\) and \(z\) represent pupil function, \(F_{ij}\) is the aberration coefficient, and the different serial numbers \((i, j)\) represent different kinds of aberrations. \(F_{ij}\) can be written as:
\[ F_{ij} = M_{ij} + \frac{m \lambda}{\lambda_0} H_{ij}, \]  

(2)

where \( m, \lambda \) and \( \lambda_0 \) represent the diffraction order, the use wavelength of the grating, and the fabrication wavelengths, respectively. \( M_{ij} \) and \( H_{ij} \) represent the use parameters of grating and the fabrication parameters of grating. In an ideal imaging system, \( F \) should have nothing to do with \( y \) and \( z \). However, the actual system has aberrations, which can only minimize the absolute value of the related parameters or cancel each other. \( F_{ij} \) is related to \( M_{ij} \) and \( H_{ij} \). Therefore, the optimization objective of flat field holographic concave grating is to minimize the absolute value of the variables that are related to \( y \) and \( z \). that is, to minimize \( F_{ij}^2 \) integral values in the range of spectral use, it can be expressed as:

\[ F_{ij}^2 = \int_{r_{\text{min}}}^{r_{\text{max}}} \left| F_{ij}(\alpha, \beta, r_A, r_B, \delta, \gamma, r_C, r_D, R) \right|^2 d\beta, \]  

(3)

where \( \alpha, \beta, r_A \) and \( r_B \) are the use parameters of incidence angle, diffraction angle, incident arm and ejector arm. \( \delta, \gamma, r_C, r_D \) are the production parameters of the space position of the recording light source. \( R \) is the radius of curvature of concave grating. The initial structure of the optical system can be calculated by replacing the different wavelengths. After initial determination of the optical path structure, the aberration and stray light are further considered. The macro function is written into the ZEMAX by the boundary condition. The simulation optimization is carried out with the incident light source, and then the incident slit is added to the optimization until the full band image spot meets the requirement. The result of the optimized design, as shown in the table 1. The optimized optical path diagram is shown in Figure 2.

Table 1. Optimal design parameters of flat field holographic concave grating.

<table>
<thead>
<tr>
<th>Use parameters</th>
<th>Production parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_A / \text{mm} )</td>
<td>92.026</td>
</tr>
<tr>
<td>( \alpha / (^\circ) )</td>
<td>-7.342</td>
</tr>
<tr>
<td>( r_B / \text{mm} )</td>
<td>88.923</td>
</tr>
<tr>
<td>( \beta / (^\circ) )</td>
<td>-25.625</td>
</tr>
<tr>
<td>( r_C / \text{mm} )</td>
<td>104.628</td>
</tr>
<tr>
<td>( \gamma / (^\circ) )</td>
<td>18.264</td>
</tr>
<tr>
<td>( r_D / \text{mm} )</td>
<td>117.396</td>
</tr>
<tr>
<td>( \delta / (^\circ) )</td>
<td>25.641</td>
</tr>
</tbody>
</table>

Figure 2. The design results of optimized optical. (a) 3D Layout, (b) Shaded Model, respectively.

The operating wavelength range of the optical system is 200–800nm. The 250nm, 500nm and 750nm near the wavelength of the Spot diagram (Figure 3) are selected to analyze the resolution of photoelectric detection system. In the vicinity of 250nm, the spot at the wavelength interval of 2nm can be seen that the two spots can be separated, so the resolution of the system at 250nm is better than 2nm. In the vicinity of 500nm, the distance between the spots is 2nm, and the separation effect is obvious. It has the best system resolution. The resolution at 750nm is about 2nm. To sum up, the
wavelength range of the photoelectric detection system reaches 200~800nm, and the resolution is better than that of 2nm, and it has a good response to the ultraviolet band.

![Figure 3. Spot diagram of a)250nm, b)500nm, c)750nm.](image)

**Summary**

In this paper, we have studied the principle of the photoelectric detection system. According to the design theory of concave grating and optimization simulation by ZEMAX software, a photoelectric detection system based on flat field concave grating is designed, which can accurately and reliably collect the continuous spectra of the 200~800nm band of the water body. Furthermore, the resolution of the design is better than 2nm, and it can be applied well with the UV-Visible spectroscopy water quality monitoring technology.

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**References**


